

July 1986

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**NASA
Technical
Paper
2547**

1986

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SUMMARY

Studies have been conducted at the NASA Langley Research Center (LaRC) to establish baseline human teleoperator interface data and to assess the influence of some of the interface parameters on human performance in teleoperation. As baseline data, the results will be used to assess future interface improvements resulting from this research in basic teleoperator human factors. In addition, the data have been used to validate LaRC's basic teleoperator hardware setup and to compare initial teleoperator study results.

Four subjects controlled a modified industrial manipulator to perform a simple task involving both high and low precision. Two different schemes for controlling the manipulator were studied along with both direct and indirect (i.e., via a television monitor) viewing of the task. Performance of the task was measured as the length of time required to complete the task along with the number of errors made in the process. Analyses of variance were computed to determine the significance of the influences of each of the independent variables. Comparisons were also made between the Langley data and data taken earlier by Grumman Aerospace Corp. at their facilities.

Significant effects were found for precision of the task, control mode, and intersubject differences. Surprisingly, the effects of viewing mode were weak or not significant at all. Control input gain was found to be very important in permitting (1) gross task elements to be performed with speed and (2) precise task elements to have the needed control fineness. Comparisons with Grumman data were generally favorable, reflecting mainly differences in the type of equipment being controlled.

INTRODUCTION

With the operational success of the Space Shuttle and the advent of the Space Station, there is a growing need to perform operations in space such as constructing large orbiting facilities or repairing, resupplying, and servicing satellites already in place. As the Space Station comes to fruition, this need will become even more acute. If reasonable alternatives are not perfected soon, much of this work will have to be done by astronauts during extravehicular activity (EVA) at potentially great cost in terms of human safety, time, and money. For instance, the space suits that astronauts must wear during EVA impose severe restrictions on the motion of their extremities and, consequently, their dexterity. Likewise, motion in these suits consumes large amounts of energy, severely limiting the length of work periods. Thus, the costs of providing transportation and life support for the army of astronauts required to build a space station through EVA would be enormous.

The most obvious alternatives to EVA are the use of either fully automatic machines or human-controlled remote machines. Either type of machine is currently available for use, but their capabilities are very limited. The Space Shuttle Remote Manipulator System, although primitive, has proven to be very effective for a variety of operations in close proximity to the shuttle vehicle with the manipulator system working alone and working with EVA astronauts. It is a classic teleoperator system in the sense that it relies primarily on the human to integrate feedback, make decisions, and input control commands. It also represents essentially the state of the

art of teleoperation technology available today for performing remote operations in space. The state of the art in fully automatic machines has advanced very little beyond the machine used on the Viking Mars Lander mission. Current automatic operations are primarily the result of sequences of human preprogrammed elemental operations with very little closed-loop control.

The automation technology research at the NASA Langley Research Center (LaRC) takes this general state of the art as a beginning from which new technology may be built to advance the state of teleoperation by enhancing both the human-machine interface to the remote equipment and the level of automation of the remote equipment itself. The research is expected to advance this state ultimately to one of supervisory control in which the human acts as a high-level goal setter and monitor with the system taking care of the detailed implementation of the tasks. The research described in this report is a first step for developing the human interface aspects of this process. It evaluates the effects of certain parametric variations with respect to a particular teleoperator interface to a Unimation Inc. UNIMATE PUMA Mark II robot. A data base is established for use as a reference against which the effectiveness of future interface improvements may be measured. The PUMA represents a new class of digitally controlled manipulators and as such is radically different from the traditional electromechanical or direct-cable-linked master-slave types of manipulators. A literature search has not uncovered any documentation of previous research on the performance of an operator interfaced to manipulators of this class. Thus, basic, new human-performance documentation with respect to such manipulators has been generated and is compared with similar performance documentation of master-slave manipulators.

We wish to express our appreciation to the Grumman Aerospace Corp., and especially to Roy E. Olsen of Grumman, for making available the results of their earlier research for comparative evaluation in the performance of this research. Mr. Olsen spent many hours advising and consulting with us in this endeavor.

Finally, the subjects in these tests were all employees of the LaRC Automation Technology Branch, with full-time duties in addition to their function as subjects. Their many comments and suggestions have proven invaluable in completing this work. We therefore express our gratitude to Kevin N. Barnes, Sixto L. Vazquez, and Marion A. Wise for their contributions to this research.

SYMBOLS AND ABBREVIATIONS

C_1, C_2	resolved-rate and joint-by-joint control modes, respectively
EVA	extravehicular activity
G_1, G_2, G_3, G_4	Grumman subjects
L_1, L_2, L_3, L_4	LaRC subjects
LaRC	Langley Research Center
P_1, P_2	0.500-in. and 0.995-in. pegs, respectively
PUMA	Programmable Universal Manipulator for Assembly
RMS	Remote Manipulator System

S_1, S_2, S_3, S_4 test subjects (in all cases Langley subjects)

SRI Stanford Research Institute

σ standard deviation

BACKGROUND

The research and development of manipulators and teleoperator systems has been promoted and stimulated primarily by the particular needs and the absolute requirements of the nuclear industries. These industries have had to put in place devices to handle radioactive materials, many of which are simply too hazardous to be handled directly by humans; however, the handling requirements of these materials has not been extremely complex. Thus, although sufficient research was performed by this industry from the late 1940's through the early 1970's to generally satisfy its own requirements, these requirements were limited, and therefore the industry did not produce manipulators of sufficiently high dexterity to satisfy its own future needs or the current needs of other industries. The research resulted almost without exception in manipulators of the master-slave type in which the human moves a multilinked arm whose changing configuration drives a replicated remote arm to actually perform the task. The advent of more powerful computers in even smaller, lighter packages in recent years has made possible many other useful applications of manipulators in both human-teleoperated and in computer-implemented-intelligence control modes. Thus, the need for additional research to develop more versatile manipulators, intelligent computing schemes for their control, and more efficient human control interfaces to them has arisen.

Among the new class of manipulators are those which have each of their joints under individual microprocessor control. These digital devices differ considerably from the older, basically analog master-slave types. They are much more precise and more suitable for partial or total computer control, but they do not naturally incorporate features such as force feedback to the teleoperator or intuitive method of control. Of course, with the computer in the loop, control characteristics can be modified with software and a large array of input devices can be accommodated. Thus, with appropriate hardware additions, amenities such as force feedback could be made an integral part of the digital manipulator's control.

The purpose of the work reported herein was basically twofold: (1) to establish a teleoperator reference data base and (2) to validate the teleoperator system setup which has been developed at LaRC. Since the system is new (and all digital), there are no comparative test results for the exact same equipment and setup. But there are results from previous tests with master-slave manipulators which can be used as guidelines to determine whether or not LaRC results are generally consistent. These comparisons can also be used to evaluate the relative worth of the two different types of teleoperator systems. An effort to find data from appropriate earlier tests focused on a set of experiments performed by Grumman Aerospace Corp. in 1982 (ref. 1). This work had the particular advantage of being strongly related to even earlier (1978) teleoperator research performed by Stanford Research Institute (SRI) International using similar master-slave manipulators and virtually identical task boards (ref. 2). A portion of Grumman's tests was chosen to be reproduced as a part of the tests at LaRC.

Grumman Studies

Figure 1 shows the Grumman Dexterous Manipulator Lab at Bethpage, New York. Here simple peg-in-the-hole tasks were performed with the subject looking both directly at the task area and indirectly at it through a closed-circuit television link. The specific task was to grasp the peg (no. 8) shown in figure 2, depress switch 1 on the task board with it, and then insert it into the receptacle (switch 9). After the peg was extracted from the receptacle, the process was repeated in sequence, alternately depressing switches 2, 3, and 4 and inserting the pegs into the receptacle. The complete sequence comprised a run. Runs were scored both by run length and by number of inappropriate contacts with the task board or with any other objects in the test environment. The manipulator used in these tests was an analog type master-slave device made by Teleoperator Systems Inc. The study resulted in the establishment of a human teleoperator performance data base for a particular, but fairly representative, industrial master-slave manipulator. Generally, better performance was obtained for the direct-view cases than for the indirect-view cases.

SRI Studies

The SRI studies (ref. 2) also utilized a task board similar to the Grumman task board. The SRI studies involved grasping different-sized metal pegs with a master-slave manipulator and performing with them any of several tasks, including depressing switches and inserting the pegs into and extracting the pegs from various receptacles. The objective of these studies was to test the hypothesis that the times required to perform elements of a task could be measured and linearly combined to predict the time required to complete composite tasks involving the same elements. The emphasis, then, was on measuring task element times such as time required to position the manipulator over the hole before peg insertion. Predicted and measured results were generally obtained.

FUNCTIONAL DESCRIPTION OF THE HARDWARE

The LaRC teleoperator experiments were performed in the intelligent systems research laboratory (ISRL) at the LaRC through use of a research version of an industrial manipulator, a task board, two control stations, computing equipment to support control of the manipulator and perform on-line data reduction, four control input devices for the human operator, and a closed-circuit television camera and monitor. Two different basic test setups were used, one for a direct view of the task board and the other for an indirect view. Subjects operated the different input devices to drive the manipulator to perform various simple operations on the task board. For those tests in which comparisons with earlier Grumman tests could be made, an attempt was made to reproduce comparable test conditions such as viewing angles and distances.

Direct-View Setup

The sketch in figure 3 shows the relative locations of major components of the direct-view test setup. The PUMA was secured on top of and near the end of a 33-in.-high table and the task board was mounted in front of it on a separate small table that was 3 in. lower; this placed the top of the task board in the plane of the PUMA base and allowed the task board to move in case a spurious signal caused the manipulator to bump it. The operator's control station was located to the left on an

adjustable-height platform. The platform was adjusted for each subject until his eyes were 81 in. above the laboratory floor (just as had been done in the Grumman tests). Consequently, the subjects looked approximately 35° to 40° downward and 50° to 55° to the right to view the task board. Figure 4 shows a subject controlling the manipulator with the attitude and translation controllers shown in figure 5. These controllers, along with the joint-by-joint controller shown in figure 6, were mounted on a shelf 40 in. above the platform floor.

Indirect-View Setup

For the indirect-view tests, the subjects and the control station were located in an acoustically isolated room that was separate from the manipulator itself. Figure 7 shows the layout of the room and figure 8 shows the displays and controls. A view of the task was presented to the subjects on an 8-in. black-and-white television (TV) monitor. The view was derived from a TV camera that was mounted approximately where the subject's eye had been when using the direct-view control station. The optical axis pointed 35° downward and about 50° to the right so that it intersected the task board near the center of its work area. Optical gain was set through zoom adjustments on the camera to fill the TV monitor screen completely with the task board. The subjects sat on an adjustable seat and operated the controls directly in front of them.

Methods of Manipulator Control

Two different schemes for controlling the manipulator were employed, each with its own particular form of control input. In the simpler of the two schemes, the manipulator was controlled one joint at a time with the joint-by-joint controller shown in figure 6. A rotary switch was used to select the joint to be controlled and a center-return toggle switch was used to command positive and negative rotations about that joint.

In the second scheme (resolved-rate control, ref. 3), decoupled rate commands were input directly into the axis system of the end effector. With his right hand, the subject operated an aircraft-type three-axis hand controller (fig. 8) to input attitude commands (pitch, yaw, and roll) to the end effector. With his left hand, the subject used a controller (similar to the one used to control translation on the Lunar Module in the Apollo Program) to input commands which caused translation to take place in the X-, Y-, and Z-axes of the end effector. Resolved-rate control causes the commanded rates to be resolved into equivalent manipulator-joint angle rates of change. A CDC CYBER 175 computer system was used during runs with resolved rate to accommodate the very complex, real-time matrix manipulations required. The input setups for both control schemes were chosen to be compatible with those used on the Space Shuttle to control the Remote Manipulator System (RMS).

Foot Pedal

A foot pedal was provided for control of input gain to permit the subjects to make efficient trade-offs between parts of the task that required gross manipulator movements and those which required very fine, precise movements. High gains could, for instance, be used when rapid movement rather than precision was more important. The pedal was located near the subject's right foot and was similar to an automobile accelerator pedal in operation except that it was not spring loaded (i.e., it stayed

where you put it). Maximum gain and consequently maximum manipulator rates for given inputs were obtained when the pedal was fully depressed.

Manipulator

The manipulator used in these studies was the Unimation Inc. PUMA UNIMATE Mark II shown in figure 9. It has six degrees of freedom, not including the end-effector jaw motion, and each of its axes, including the end effector, is under individual microprocessor control. It has very little slop or compliance and a repeat positioning accuracy of ± 0.004 in. The end effector (shown in fig. 10), which is the parallel-jaw type, was used only as a holding fixture in these studies. Its operation otherwise was not involved or considered as an influence in the experiments.

Task Board

A task board (fig. 11) was built to accommodate simple, precise tasks. It was modeled after the one constructed by SRI International and can be used for a variety of tasks that involve activating switches (spring-loaded push type) and placing various-sized cylindrical pegs in cradles and cylindrical receptacles. The board was equipped with sensors that activated indicator lights on its surface as well as signalled data-reduction software upon completion of basic task elements; thus, it provided both real-time data signals and operator feedback. Two different cylindrically shaped pegs with diameters of 0.995 in. and 0.500 in. (fig. 11) were supplied, giving both a loose and a very close tolerance fit when they were inserted into the 1.000-in. cylindrical receptacle in the upper right corner. A microswitch at the bottom of the receptacle was activated when the peg was fully inserted. Although the smaller peg was much easier to insert and extract from the cylindrical receptacle, it was harder to position squarely onto the switches. Overhead fluorescent lights provided approximately 22 footcandles of light at the task board. For more detailed descriptions of the hardware used in these experiments see appendix A.

DESIGN OF EXPERIMENT AND PROCEDURE

The tests described in this report were intended more to characterize the utility and efficiency of a particular teleoperator system and its interface to establish a reference data base rather than to test a particular hypothesis relative to its operation. In addition, these tests were also expected to generally validate the teleoperator research facility in the ISRL at LaRC. The tests conducted were a basic set intended to investigate the influence of certain interface-element variables on the overall effectiveness of the human to remote-manipulator interface. The variables selected for investigation included control algorithm, preciseness of the task, and view (direct or indirect). The objective was both to quantify the effectiveness of the present interface and to relate it and its associated manipulator hardware to the effectiveness of other teleoperator systems.

Interface

Two different interfaces (one for direct viewing and the other for indirect viewing, as discussed previously) were established between the human operator and the remote manipulator. These interfaces differed in the configuration of the hardware through which the operator made control inputs and whether the operator viewed the

manipulator directly or through a closed-circuit TV link. The influence of these two interface variations was studied along with the influence of task difficulty, which was dictated by the closeness of fit of the two different-sized pegs to their receptacles.

Task

A simple task was selected for its generic character and compatibility for comparison with earlier studies. The task consisted of the operator using the manipulator to depress switches on the task board with either of two different-sized pegs, followed by the insertion of the peg into a receptacle. Specifically (see fig. 11) the sequence for each peg was depress switch 1, insert peg in receptacle, extract peg, depress switch 2, insert peg in receptacle, and so forth, continuing this pattern through switch 4. When this task was tried manually to find out how difficult it might be to perform ordinarily, the human operators found it easy to perform directly with their own hands, even with the larger peg, but they also found that the larger peg did require some obvious attention which was not required for the smaller peg.

Runs

The test matrix in table 1 shows the eight basic run conditions used for each subject to cover all the various combinations of the three parameters being studied. Ten replications of each of these runs were made for each subject to form a data set. Runs were made in random order except that the direct- and indirect-view runs were performed sequentially because of the impracticality of switching back and forth from one setup to the other on a run-by-run basis. The direct-view runs were performed first.

Subjects

Four male subjects whose ages ranged from 22 to 56 were selected on the basis of demonstrated aptitude for the task. Their background education and experience was technical. It was felt to be desirable and more beneficial to NASA to test subjects with particular aptitude for the task than to test the skills of the general population because NASA is more likely to have available and to use highly skilled and well-trained operators. The subjects were given an orientation sheet (reproduced in appendix B) which explained the purpose of the study, the procedures to be followed, how the runs were to be scored, and so forth.

Training

Subjects were given extensive training to eliminate learning effects. Table 2 contains approximate training times which were acquired in practice sessions of approximately 30 minutes per subject. The amount of training needed to reach plateau performance varied from 450 to 697 minutes for direct-view setup and from 240 to 444 minutes for indirect-view setup. Required training level was determined both by the individual subject's belief that he had reached the performance plateau and by the concurrence of the experimenter or observer. Subject 1 also participated as a development subject in setting up, refining, and fine-tuning the manipulator hardware and interfaces. This participation accounts for some of his training time, which

might be more legitimately called experience than training. The data for direct-view setup were taken immediately following direct-view training, which was completed before indirect-view training commenced.

Initial Conditions

The initial conditions for these tests consisted primarily of a particular starting position and attitude to which the manipulator was driven before the beginning of each run. Essentially the initial condition positioned the end effector with the peg already in its jaws slightly above switch 1 and slightly forward of the task board. The intent was to minimize the amount of maneuvering required before the depression of switch 1, the point at which task measurement began.

Scoring

Two different performance measures were used to score the runs. The first was the length (time) of the run, which was measured directly by the computer from electrical outputs to it from the task board. Specifically, the run length was the amount of time between the depression of switch 1 and the fourth activation of the microswitch at the bottom of the receptacle. The second measure was the number of impacts that the subject caused to occur between the manipulator-held peg and other objects in the task area during a run (other than those impacts which were legitimately part of the task). These impacts were counted by human observers. Subjects were told to achieve the best compromise between speed and accuracy without being given any further definition of what the compromise might be.

RESULTS

The results of these tests consist of measured times needed to complete the task, number of inappropriate contacts between the manipulator and objects within the task environment, and general observations by the investigators and the subjects. The objective measures are tabulated in tables 3 and 4, which also include means and standard deviations calculated for each condition for each subject. Analyses of variance (ref. 4) were performed for much of the data to determine the statistical significance of various comparisons. Analyses were performed on the data grouped by viewing setup. Direct-view runs were analyzed first. The indirect-view runs were analyzed next, and then all the objective data were analyzed as a whole. Raw data from Grumman's earlier studies were obtained and processed at Langley for comparison with the LaRC data.

Analysis of Direct-View Data

Figures 12 and 13 show task completion times and impact data from the LaRC direct-view tests and from studies conducted by Grumman. It was previously pointed out that the LaRC subjects had extensive training. This was not the case with the Grumman subjects, however, for whom all runs were used for both training and data. Each Grumman subject made 20 runs for each condition. For these analyses the last 10 Grumman runs were used to compare with the 10 LaRC data runs because examination of run-by-run plots of the Grumman subjects' individual data suggested that near-stable performance was achieved during the last 10 runs. The LaRC data are for the 0.500-in. peg and for resolved-rate control, which was felt to be the most similar of the two LaRC control modes to the Grumman master-slave control. Although the mean

task completion times differ by about 25 percent, they are intuitively acceptable because they imply that the times are consistent and that no great error has been made in the setup and measurement. But the data for number of impacts are very different; the LaRC data have a mean of 0.33 impacts per run whereas the Grumman data had 2.40. The data for impacts are believed to differ so greatly primarily because of the great differences in the dynamic response characteristics of the manipulators. (See section entitled Discussion of Results.) The results of an analysis of variance performed to compare LaRC direct-view data with Grumman direct-view data are shown in table 5. They indicate significant differences at the 99-percent confidence level for both task completion time and number of impacts.

LaRC data for the direct-view condition were also analyzed to assess the effects of peg size and control mode. An analysis of variance based on task completion time indicates that significant differences at the 99-percent confidence level exist for every variable tested as well as their interactions. (See table 6.) The analysis of variance based on number of impacts (table 7) shows significance only for subjects and peg size. In our opinion, however, this measure (number of impacts) is probably a much less sensitive performance index than task completion time.

Figure 14 shows the effect of control mode on task completion time for the direct-view setup. The bars are mean values for all subjects computed for all other variables in the direct-view setup. The values indicate resolved-rate control was much better than joint-by-joint control. Subject comments also reflect this. (See appendix C.) The mean number of impacts as plotted in figure 15 favors resolved-rate control as well, but only slightly. As expected, the effect of peg size is statistically significant for both measures, as illustrated in figures 14 and 15. Inserting the 0.995-in.-diameter peg in the 1.000-in. receptacle is much more difficult than inserting the 0.500-in.-diameter peg, obviously requiring more time and accuracy. However, the 0.500-in. peg was more difficult to position on the switches in order to push them, a disadvantage which was somewhat unexpected and which is less important than the advantages shown for this peg size.

Examination of the data in figures 16 and 17 (all the direct-view data plotted subject by subject) suggests that one subject performed very differently from the others. Apparently this subject emphasized speed of performing the task at the expense of accuracy much more heavily than did the other subjects. Noting this and being very concerned particularly about there being statistically significant performance differences among subjects, we decided to reapply the analysis of variance to data for just the other three subjects. The results are presented in tables 8 and 9. Note that now subject variation is no longer significant on either measure. Fewer interactions are significant, but the previously most significant variables of peg size and control mode are still quite significant.

Analysis of Indirect-View Data

Figures 18 and 19 for the indirect-view tests show about the same trend as shown in figures 12 and 13 for the direct-view tests. Also, figures 20 and 21 show trends similar to those shown in figures 16 and 17. The analysis of variance shown in table 5 indicates both the mean task completion times and the number of impacts differ significantly between the LaRC and Grumman tests.

Tables 10 and 11 contain the results of an analysis of variance for the LaRC indirect-view data. Note that the three-variable interaction of subjects, peg size, and control mode is not significant for task completion time, although it was for the

direct-view tests. The impact results, however, show significance for control mode which was not present for direct-view tests. A recomputation of the analysis of variance for three subjects was also carried out as for the direct-view data, but it did not eliminate the significant difference among subjects as it did for direct-view data.

Analysis of All Data

Finally, all the LaRC data are considered as a whole. Perhaps the most important result from the analysis of variance for both task completion time and number of impacts (tables 12 and 13) is that there was no statistically significant difference between runs made in which the subjects viewed the task area directly and runs in which they viewed the area indirectly through the TV link. This is particularly interesting considering the fact that the other main variables, including subjects, show strong significance for both measures. Also, in the case of task completion times, all interactions of variables are significant. If the confidence level were reduced to 90 percent, view and its interactions with subjects, peg size, and control mode would be significant for task completion time. However, doing the same thing for number of impacts would produce a significance only for the interaction of subjects and view. Even a reduction in confidence level to 75 percent will not produce significance for the view variable for number of impacts.

All the data for each of the LaRC test subjects were lumped and means and standard deviations were computed for both task completion time and number of impacts. These data are shown in figures 22 and 23. Note the large differences between subjects, especially between subject 1 and the rest of the subjects. However, an analysis of variance for subjects 2, 3, and 4, as was previously done for direct- and indirect-view data, shows highly significant intersubject differences even with data for subject 1 omitted. Figures 24 and 25 show the overall effect of peg size on task completion time and number of impacts, respectively. As in the preceding analyses, the larger peg requires more time and causes more impacts. Figures 24 and 25 also show the overall effect of control mode on task completion time and number of impacts, respectively. The plot for task completion time strongly points to the greater usefulness of resolved-rate control for this task, whereas the plot for number of impacts indicates very little effect of control mode.

DISCUSSION OF RESULTS

The results of these tests generally satisfy the study objectives and are in harmony with intuitive expectations. One of the objectives was to validate the operation of LaRC's manipulator system through operational comparisons with earlier studies performed by Grumman Aerospace Corp. This objective has been satisfied and a substantial data base has been established, including statistically analyzed indices of performance, video-taped runs, and logs of subject comments, all of which may be used as a reference against which future teleoperator research advances can be evaluated. The results are discussed individually in sections that follow.

Direct Versus Indirect View

The lack of performance degradation through use of the closed-loop television link is perhaps the most unexpected result to come from these tests. Because this result was found, a reexamination of the Grumman data was made to see if a similar

trend could be found there as well. It was not. The differences for view for task completion times are significant at the 99-percent confidence level, whereas the differences for view for number of impacts are significant at the 95-percent confidence level. Of course, with the Grumman data the consideration is for a much more constrained data set than for the larger LaRC total data set, from which the conclusion of no significant difference was derived. An examination of the portions of the LaRC data set which are directly comparable to the Grumman data yields a result much more consistent with that of the analyzed Grumman data. In both the LaRC and the Grumman data there are slight increases in task completion times from direct to indirect view which are significant at the 95-percent level. Although both the LaRC and the Grumman data show large-percentage increases in number of impacts from direct to indirect view, only those for Grumman are statistically significant. The LaRC data for this condition are not even significant at the 75-percent confidence level.

Interestingly, there are actually some reversals of the above trends found in the analysis of the LaRC "total" data set. Both task completion time and number of impacts decrease from direct to indirect view. The difference in task completion time is so small (221.80 sec to 211.76 sec), however, that intuitively one would never believe their difference is meaningful. Even so, the analysis of variance indicates significance at the 90-percent confidence level, which is fairly high but, for the purposes of this report, is too low (below 95 percent) to be considered statistically significant. The difference in number of impacts (1.31 to 1.10), on the other hand, is not significant even at a 75-percent level. The generally lower confidence levels for significance, small differences in means, and the reversal of trends when a larger data set for more variables is analyzed suggest that, from a statistical point of view, there may have been no clear performance differences because of view for these studies. Even so, these objective measures do point to somewhat decreased performance for the indirect view. Comments made by the subjects during the runs, as well as more formal comments presented in appendix C (1 to 3), strongly suggest that the indirect-view runs were more difficult for them. It is often the case that humans adjust to a more difficult task for themselves by increasing their work load while performing about as well as before. Thus, in some comparisons, statistically analyzed objective measures may show little or no performance differences, even though they are there. This probably happened in these tests. Also, as discussed subsequently, the subjects had to develop a procedure to allow themselves to align the peg normal to the task board for insertion in the indirect-view setup because they could not do it with sufficient preciseness visually. If these "alignment" times were somehow measured and added to the indirect-view task completion times to properly account for their contribution, the indirect-view times would increase, probably causing the objective performance measure to show the indirect view to be more difficult.

Thus, one is led to conclude for the conditions of this experiment that probably there is an important effect from direct versus indirect viewing of the task, but it is weak. The lack of significant difference indicated for view in the LaRC data may be partly a consequence of the basic viewing conditions in the test setup. The most critical part of the task was the insertion of the peg into the hole. But during this operation the subject's direct view was such that the end-effector pitch was mainly in a plane orthogonal to the plane of the subject's eye, thus diminishing his ability to perceive the pitch of the end effector. This condition caused subjects to often attempt insertions with the end-effector pitch at impossible angles. Since the indirect-view setup had the TV camera placed at exactly the same position as the subject's eye was for the direct view, a similar problem was present for the indirect view as well. Yaw of the end effector was largely in the plane of the eye (camera view) in both cases. The distance of the end effector from the subject and the

symmetry of the peg probably diminished the effectiveness of stereoscopic vision for the direct-view setup. Therefore, greater resolution and color may have been the only important optical advantages to direct view. There were, however, other perceived minor advantages, such as auditory clues.

The effects of training were also in all likelihood very important. The extensive practice time given to the subjects may have trained away the differences due to viewing conditions. (See page 8 for Grumman training conditions.) If this was the case, it suggests that either the differences were not all that great or the subjects learned to do the task but with a much higher work load. The suggestion of a higher work load assumes the indirect-view task was more difficult, which was subjectively observed from subject comment as well as intuitively expected. Note from table 2 that stable performance for indirect view was reached in less time than it was for direct view. This may have resulted from the training for aspects of the task that were common to both viewing setups having already been satisfied in the practice runs for the direct-view setup.

Control Mode

Objective analyses as well as subjective observations have shown resolved-rate control to be generally far superior to joint-by-joint control, but we believe joint-by-joint control has important advantages which warrant its retention as an ancillary method of control. Primarily it is needed for configuration (links of the manipulator arm) control, which is required for confident, predictable total control. For example, situations requiring control of this type occur in certain close-tolerance, delicate operations in which very deliberate, totally predictable manipulator motions must be made to perform an operation without damaging the piece being worked on. These situations might involve reaching into and around obstacles. There may be only one configuration of the manipulator-arm links compatible with the job being done and the obstacle pattern of the environment in which the arm is working. In these situations resolved-rate motion algorithms do not necessarily ensure that the needed arm configuration will be the one that results.

Much improved schemes for implementing joint-by-joint control can probably be developed. Even so, under the best of circumstances, this type of control is likely to be awkward and difficult but necessary. The particular scheme used in this work was chosen to be compatible with that used on the Space Shuttle to control the Remote Manipulator System (RMS). Our next implementation will probably use individual switches for each finger, which will permit the operator to function without looking at the controls and to make multiple, simultaneous inputs to the system.

Peg Size

The task was much more difficult with the 0.995-in.-diameter peg than it was with the 0.500-in.-diameter peg in all combinations with other task variables. This was expected because the alignment to be made with the 0.995-in.-diameter peg was very critical and the cues to effect the alignment were weak. The task was entirely visual; there was no force feedback. Even the visual information was not good in several respects. Both the distances involved and the shape of the peg minimized the possible benefits of stereoscopic vision for the direct view. The subject's viewing angle diminished end-effector pitch perception greatly in both direct and indirect view, as previously discussed.

For the indirect-view setup, the subjects developed during their training an alignment procedure to establish with the peg a vertical attitude with respect to the task board. The use of the procedure was very beneficial for inserting the peg into the receptacle. In fact, the subjects probably could not have done the task without it. This procedure, found by the subjects through trial and error, basically solved the pitch-perception problem by their following a definite sequence of operations which resulted in the manipulator holding the peg orthogonal to the plane of the task board. Virtually perfect perpendicular alignment was required to insert the peg. Essentially the alignment procedure consisted of adjusting end-effector attitude to align the peg roughly perpendicular to the task board and then, with the tip of the peg slightly above the board, translating the peg in two straight-line, orthogonal paths across the board surface. The change in the width of the gap between the end of the peg and the task board surface was noted and end-effector attitude adjusted to minimize the change. Thus, although accurate perception of attitude was not directly available, indirect cues could be generated to make up for the deficiency. In a realistic, operational task this kind of procedure is very costly in time. Our experimental measures did not account for it, however, because subjects performed the procedure before beginning the timed part of the task (i.e., before depressing switch 1). It is also true, however, that the need for the procedure is likely sensitive to the subject's viewing angle. Thus, one should be cautious and accountive of this factor when applying and interpreting these data. In fact, the proper accounting of this factor (not at all obvious what this accounting is) might alter some of the conclusions concerning the effect of view.

Intersubject Performance Variability

In almost all cases the subjects performed significantly differently from each other. This was true of both the LaRC subjects and the Grumman subjects. It had been expected that, at least in the LaRC studies, the selection process and the large amount of training would have minimized intersubject differences, and perhaps they did. But if they did, the effect was not sufficient to overcome the inherent intersubject differences. Probably in itself this issue is worth further study. We are reasonably certain that task interpretation had a large influence on the performance of one of the LaRC subjects who expressed verbally that he was minimizing task completion time at the expense of all other considerations. The effect of this approach is readily evident in the various bar charts presented throughout this report. This difference in interpretation was unfortunate because with only four subjects unusual behavior on the part of one can greatly skew the composite performance of the group and very likely did in this case. Most of the cases were reanalyzed with the different-performing subject's data omitted. Even so, in only the direct-view case was intersubject variation altered to be not significant as a consequence of doing this. Thus, it must be concluded that subject variations are large for these tasks, particularly since Grumman's results also show much intersubject variation.

Comparisons With Grumman Results

Comparisons of LaRC task completion times with Grumman times were in general very good. The Grumman times were somewhat lower, but the LaRC data contained fewer impacts. We believe the primary source of these differences was the difference in dynamic characteristics of the manipulators, each of which have both advantages and disadvantages. The naturalness and compliance of the master-slave manipulator as configured by Grumman probably contributed importantly to the lower task times. Conversely, lower motion damping (loop gain) and higher input gain were likely causes of

the greater number of impacts. The low loop gain increased the difficulty of moving the end effector rapidly from one place to another without an overshoot. At the same time the input gain sensitivity made small, precise manipulator movements more difficult because an even smaller (by a factor of three) hand movement was required.

Gain Control

Although not included in the studies as a parameter to be explicitly evaluated, variable gain control was observed to be quite beneficial for performing insertions without it and extractions with the close-tolerance peg. It was also important with the 0.500-in. peg to make the alignments necessary to push the buttons. The alternative without it would have been to do the entire task at a low gain, which would have greatly increased the task completion times because of the slow rate at which gross movements would have had to have been made. Not all the subjects liked the foot pedal method of implementation nor did they all prefer continuous gain control. One suggested, for instance, that three levels of discrete gain control might be preferable. These could be implemented for hand or foot actuation. The primary advantage would be that the operator could quickly and exactly return to a gain which had previously been found to be satisfactory. The continuous foot pedal was, in contrast, very general. What might be useful is a hybrid system which permits the operator to determine and set discrete levels using a separate continuous control. This arrangement would afford fast return to previous settings and still retain the generality of continuous control.

CONCLUDING REMARKS

A substantial data base has been acquired which quantifies the current manipulator system setup at Langley Research Center (LaRC) in terms of the facility with which human operators are able to use it in the performance of a basic, generic, readily repeated task. These data constitute a baseline or reference to be used for measuring the effectiveness of future enhancements to the setup or to the operator interface.

A number of interesting trends and results that were uncovered should be further considered by future researchers who add their results to the statistical base. One of the most interesting is the apparent lack of influence from the substitution of a TV view of the task for a direct view by the subject. This result needs further study to clarify and verify the explanations we have given for our having found it to be of so little consequence. Likewise, additional studies would be useful to confirm that intersubject variations in teleoperator tasks usually are as great as we found them.

Test results have generally validated the manipulator at LaRC in terms of their consistency with results obtained previously at other laboratories. As expected, resolved-rate control was found to be much easier, faster, and, for the most part, more satisfactory than joint-by-joint control. Tasks which involve operations with greater precision were found to be more difficult, again as was expected.

We believe that a common task for which teleoperator research results from different groups can be compared and related is especially important to permit one to judge and verify their results in a larger context. It would also enhance the

ability to make general inferences from several teleoperator studies. Thus, we feel it is important to use some such standard in the future, whether it is the one used here and by the Grumman Corp. or some other standard.

NASA Langley Research Center
Hampton, VA 23665-5225
January 27, 1986

APPENDIX A

HARDWARE, APPARATUS, AND EQUIPMENT

UNIMATE PUMA Mark II Robot

The PUMA used in this experiment was designed to be used in "pick-and-place" type industrial operations and was augmented with a parallel-jaw end effector. The PUMA is a six-degree-of-freedom, digitally controlled robotic arm with electrical servos. The PUMA was configured to provide shoulder tilt, elbow tilt, and wrist tilt and finger twist, wrist twist, and waist twist coordinated by a hierarchical control system composed of a master and six slave microprocessors, each slave providing low-level servo control of one joint of the manipulator. In the delivered configuration, the master controller contained a DEC LSI-11¹ microprocessor with 128 000 bytes of random access memory and 840 000 bytes of read-only memory containing a VAL operating system (a computer-based control system and language designed specifically for use with Unimation Inc. industrial robots). This delivered system allowed only limited interaction with the external environment. Although the VAL operating system is adequate for most industrial applications, it does not allow the flexibility necessary for a research environment. To obtain the requisite flexibility, the read-only memory-based controller card was replaced through in-house modifications at LaRC. The new software included functions for manipulator initialization position, rate control of individual joints, and command interpretation. Routines are available for coordinate transformations, resolved-rate control, and extended input/output.

End Effector

A microprocessor-controlled robotic end effector, based on a University of Rhode Island mechanical design (fig. 10), was used with the PUMA. The gripping surfaces of its two fingers remained parallel for all jaw openings because of its parallel actuator mechanism. The parallel actuator mechanism was actuated by sector and worm gears driven by a direct-current torque motor mounted in the base of the end effector. The end-effector parallel jaws were lined with General Electric RTV compound molded in the shape of the 0.995-in. peg. This condition gave a more resistant contact surface to control the slipping of the jaws on the smooth surface of the stainless steel pegs. To control the jaw opening rate and position feedback, information was obtained from a tachometer and an incremental shaft encoder tied to a microprocessor. Mounted in the fingers of the end effector were infrared proximity sensors which were scanned by the microprocessor to detect nearby objects to avoid collision and to detect the workpiece. Also mounted on the finger supports were strain gages to sense the force and torque applied to the fingers. Data from the strain gages consisted of normal and side forces and pitch and yaw moments from each finger. Additional force and torque information was available from a six-degree-of-freedom sensor mounted on the wrist. This wrist sensor was also controlled by a microprocessor that provided software control of calibration, coordinate transformation, and data transfer. Because of the simplicity of this experimental task, a number of the above capabilities of the end effects were not used.

¹DEC and LSI-11 are trademarks of Digital Equipment Corporation.

Task Board

The task board shown in figure 11 was built at LaRC to conform to the dimensions of the task boards used by the Grumman Aerospace Corp. and by the Stanford Research Institute (SRI) International. The task board was instrumented for several different tasks with a variety of peg tolerances and movement distances. The task in this experiment used only two of the pegs, the large one with a diameter of 0.995 in. and the small one with a diameter of 0.500 in. The dimensions and placements of the four push buttons and the receptacle that was used in this task are illustrated in figure A1.

The switches (1 to 4) used on the task board were single-throw, double-pole, momentary-on push buttons which gave two signals when pushed: (1) a visible light to indicate that the switch was pushed and (2) a discrete signal to the computer that recorded time into the test that the switch was pushed. A similar switch indicated when the peg was inserted into the receptacle. The LaRC task board was designed on a chassis 17 in. long, 13 in. wide, and 3 in. deep. The receptacle was made of stainless steel with a diameter of 1.000 in. The task board was painted a light gray and had plastic tips on the switches for contrast and to reduce reflections.

Teleoperator Direct-View Control Station

The teleoperator direct-view control station (fig. A2) was an adjustable platform on which the subjects stood to perform their tasks. The platform was adjusted to maintain an eye level height of 81 in. above the floor for each subject. Mounted on a shelf, 40 in. above the adjustable base, were three hand controllers used to control the manipulator in resolved-rate and joint-by-joint motion. In addition, wire communications, a foot pedal gain controller, and the necessary power supplies were mounted on the station. The foot pedal gain controller worked like an accelerator of an automobile as it functioned to change the rate of commanded movement to each joint. The location of the direct-view station was to the left rear of the PUMA to position the operator 3 ft to the rear of the task board and 4 ft to the left (fig. 3).

Teleoperator Indirect-View Control Station

The teleoperator indirect-view control station (fig. 8) is reconfigurable for many different tasks that will eventually be controlled from it. The control station is located in a separate room adjacent to the main laboratory (fig. A3), where the manipulator and support equipment are located. The size of the room where the control station is located is approximately 8 by 10 ft with an observation window of 2 by 3 ft overlooking the large layout table where the PUMA is mounted. The control station consists of three 19-in.-wide racks which are 5 ft high with a 19-in. protruding shelf 30 in. from the bottom. Mounted in or on this shelf are the three hand controllers used to control the manipulator in resolved-rate and joint-by-joint motion. Mounted in the three racks are numerous video monitors, including an 8-in. black-and-white monitor used to duplicate the type of monitor used at the Grumman Aerospace Corp. during the performance of their tests. The control and mode selector mounted at the top of the right rack will allow the gain to be controlled with either a foot pedal or a hand-set potentiometer.

Hand Controllers

The translation hand controller shown in figure 5 was manufactured by Honeywell Inc. for the Lunar Module (LM) in the Apollo Program. All three controller axes spring-return to center. Side-to-side, up and down, and in and out motion of the controller handle operate internal switches to generate discrete signals which are input to resolved-rate equations on the real-time computing system at LaRC.

The rotational hand controller (fig. 5), manufactured by Bosch Corp., is a three-axis controller with 10 000 Ω center-tapped precision potentiometers. It is used as a proportional output device to establish end-effector attitude through control of joints 4, 5, and 6 of the PUMA.

The two hand controllers were used to make operator inputs in the resolved-rate mode. In this mode, the control system was designed to function as if the operator were "flying" the end effector like a pilot might fly a spacecraft. This was done by the operator imagining himself to be in a cockpit contained within the plane of the end-effector jaws and looking forward along the major axis of the jaws toward the opening between the jaw teeth. If the vehicle had wings, as the Space Shuttle does, they would lie in a plane normal to the plane of the end-effector jaws. Thus, pitch would be a rotation about the axis of the wings, for example. Translational inputs caused translations to take place as shown in figure A4.

The controller for the joint-by-joint mode (fig. 6) was designed to be functionally similar to the backup control system of the Space Shuttle Remote Manipulator System (RMS) arm. This controller consists of a rotary selector switch to select the individual joint to be controlled and a spring-loaded, return-to-zero switch (a power-window switch from an automobile). The output of the controller is in the form of logic signals designating the joint to be controlled and the direction of commanded rotation.

The control scheme and placement of the controllers were designed to be general. However, if the particular task performed in these studies is examined in isolation from other potential tasks, the hand controller orientation for it might seem unnatural. This comes about because the task board was oriented in a horizontal plane, with it being necessary to perform the task to orient the end effector normal to the board. In this orientation, the controller input directions are rotated 90° from the corresponding end-effector motions.

Camera and Video Equipment

The SMF Tricon color video camera model DXC-1800 was manufactured by Sony Video Communications. The high-performance 2/3-in. SMF Tricon tube provided low lag and high sensitivity for a single-tube camera. The camera operated with Electronic Industry Association (EIA) standard National Television System Committee (NTSC) color with a scanning system of 525 lines, 2:1 interlace, and 30 frames. The picture quality was superb, with better than a 48 dB signal-to-noise ratio and a horizontal resolution of 300 lines. The zoom lens used was an F/1.4, model VCL-1106YB manufactured by Sony with focal lengths of 11 to 70 mm and with automatic and manual iris adjustment. Other features of the camera included a built-in color bar generator, automatic beam optimizer, automatic gain control, automatic white balance adjustment, and automatic black level. The camera was used with a Sony CCU-1800 camera control unit with full remote control capabilities.

Lighting

Lighting in the laboratory area came from overhead fluorescent lights yielding approximately 22 footcandles of luminance at the task board for both views (direct and indirect). This amount of lighting gave reflection that the operators used as an alignment clue, especially in the joint-by-joint mode and the indirect-view setup. The only light in the control room came from the illumination of the television monitors and the observation window to the left side of the operator, yielding approximately 2 footcandles of luminance at the hand controllers.

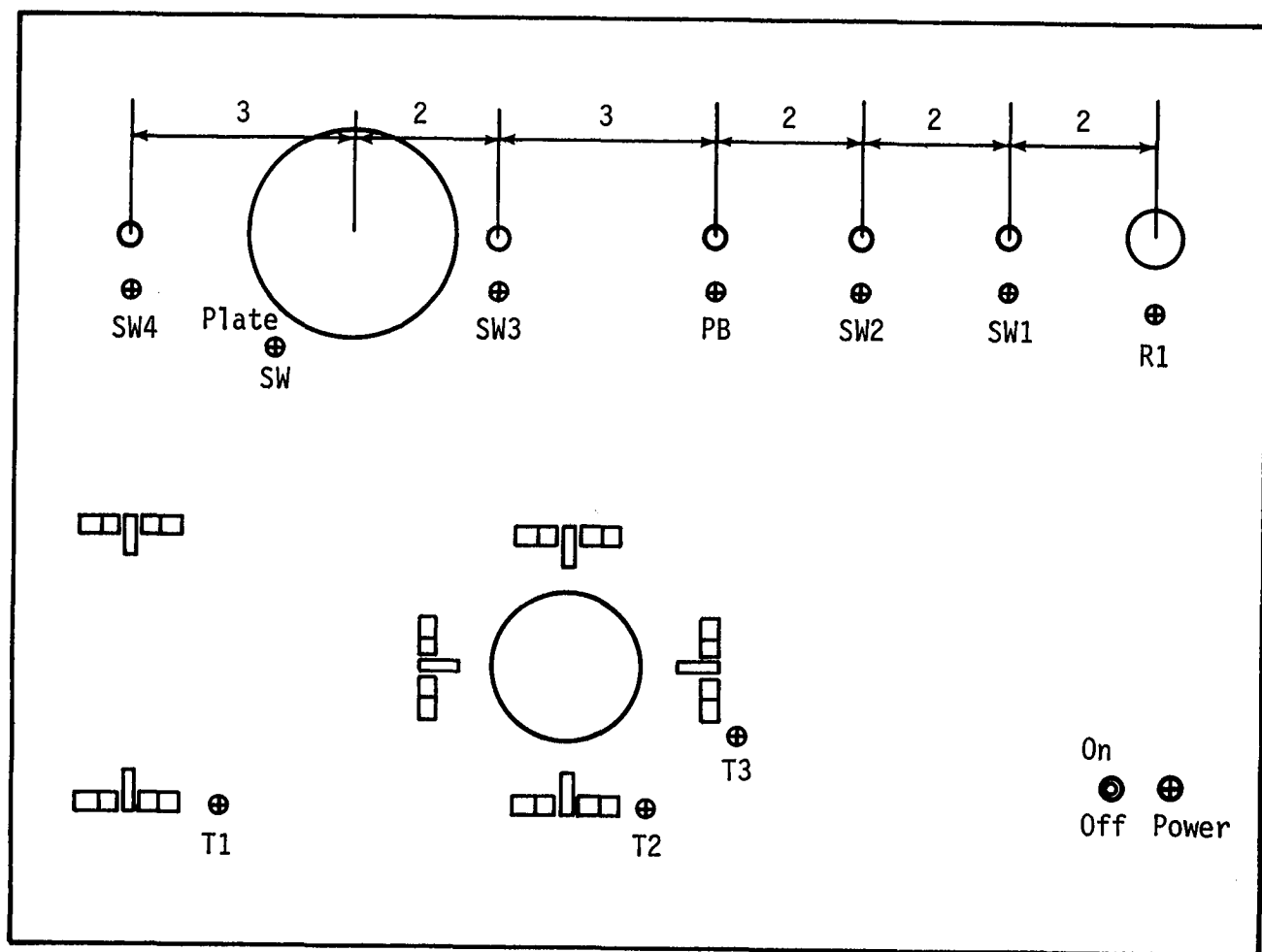
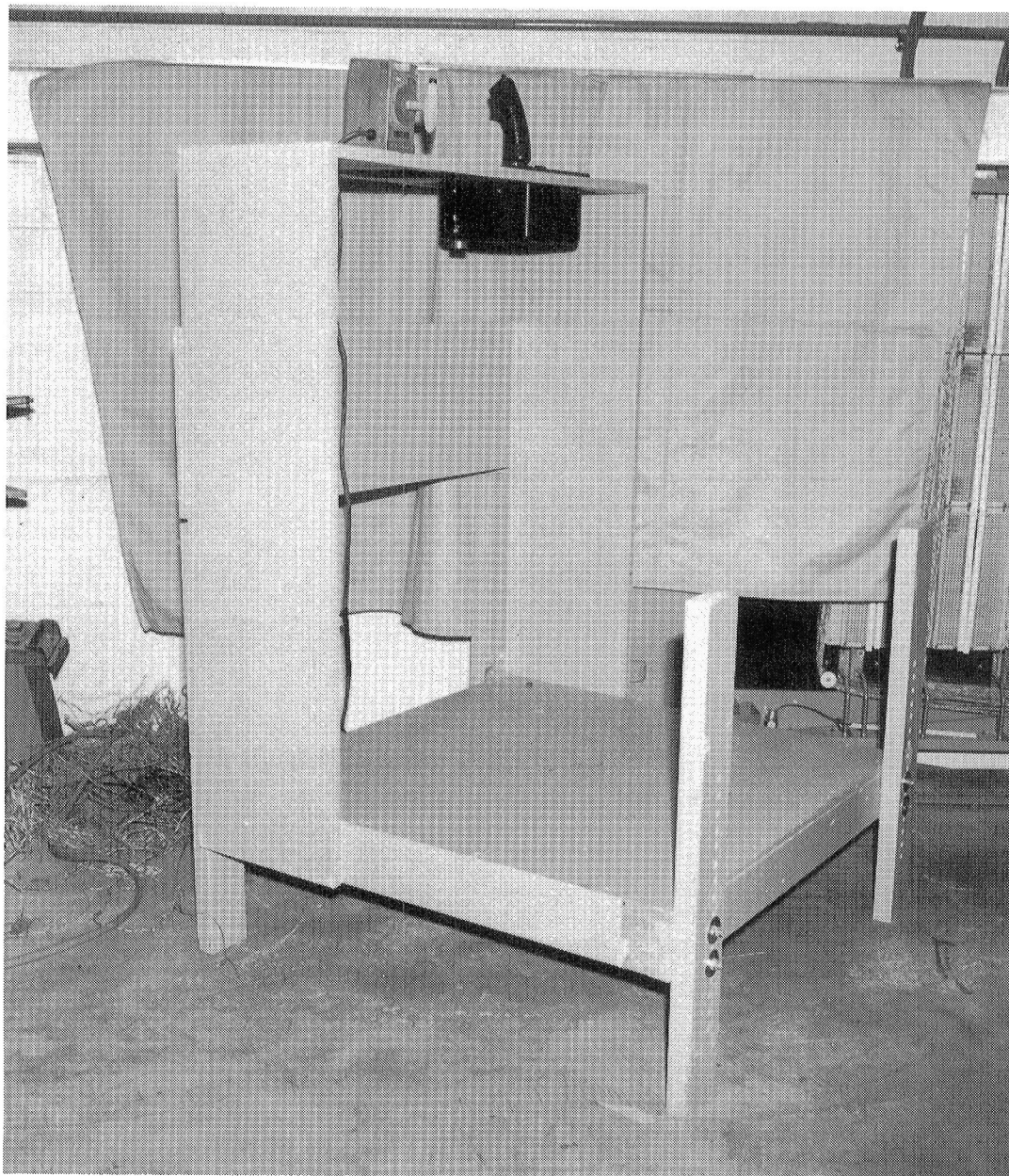


Figure A1.- Task board layout. Dimensions in inches.



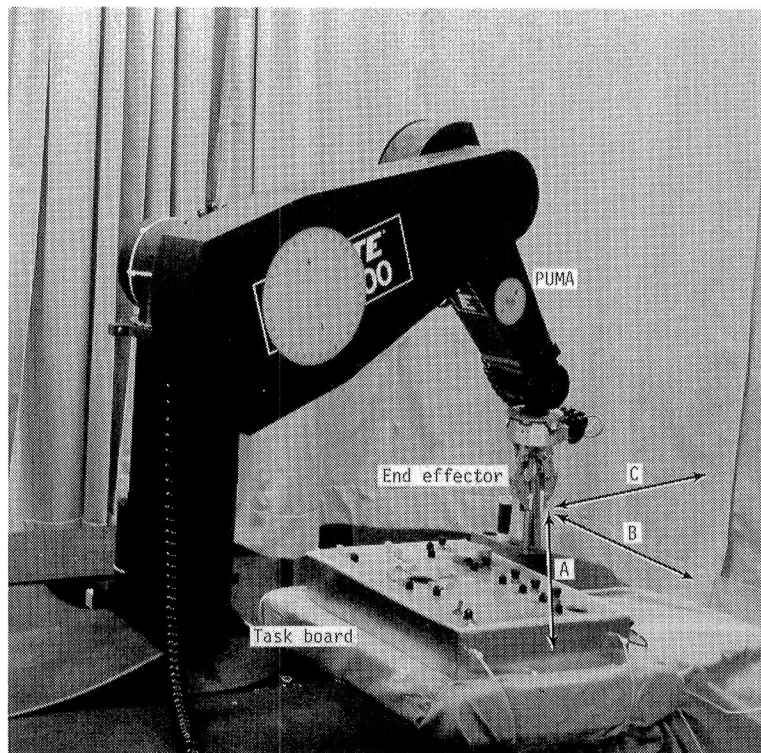
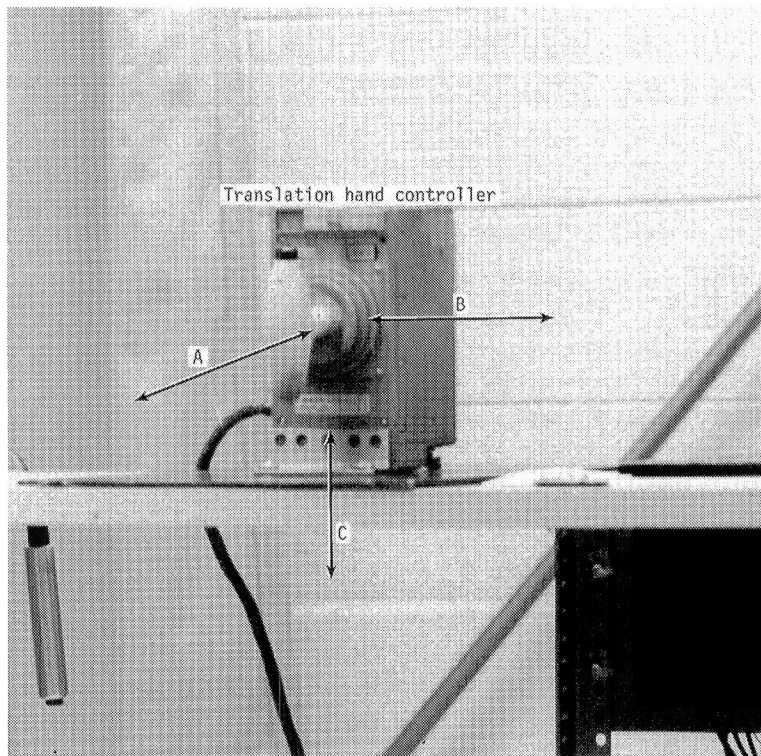
L-85-7054

Figure A2.- Teleoperator direct-view control station.



L-84-8998

Figure A3.- Teleoperator research facility in intelligent systems research laboratory at LaRC.



L-86-304

Figure A4.- Translation control relationships for resolved-rate implementation.

APPENDIX B

BASELINE TELEOPERATOR EXPERIMENT SUBJECT ORIENTATION

The following is the set of instructions and general orientation sheet given to the subjects prior to the beginning of their participation in the experiments described in this report.

The purpose of the experiments in which you are about to participate is to measure the quality of control of the PUMA manipulator as configured for these experiments. A standard task, performed previously with other manipulators, will be used to generate data for comparisons with these previous tests. From these data, a baseline performance index for the PUMA relative to other tested manipulators will be computed.

You are asked to perform the standard task in eight different situations. In addition, you will perform the task five times for each combination of independent variables. The following table shows the combinations of independent variables which define each of the eight experimental conditions.

	View		Peg size		Control mode	
	Direct	Indirect	Large (0.995 in.)	Small (0.500 in.)	Joint by joint	Resolved rate
1	x		x		x	
2	x		x			x
3	x			x	x	
4	x			x		x
5		x	x		x	
6		x	x			x
7		x		x	x	
8		x		x		x

The task to be performed consists primarily of retrieving with the end effector attached to the PUMA manipulator (see sketch, fig. B1) a small cylindrical peg and moving it to various positions on the task board (fig. B2). The experiment conductor will show you the exact sequence of subtasks after you have thoroughly studied this document. The task consists of the following actions (see task board sketch):

1. Commence after a 5, 4, 3, 2, 1, go count from the experiment conductor.
2. Retrieve peg of appropriate size from peg holder. Keep major axis of peg aligned with major axis of the end effector.
3. Position peg over switch 1.
4. Depress switch 1 activating its light.
5. Position peg over receptacle.

6. Insert peg into receptacle activating its light.
7. Extract peg from hole.
8. Position peg over switch 2.
9. Repeat steps 3-7 for each of the switches 1-4.
10. The task will end when the computer senses the activation of the receptacle switch after switch 4 has been pushed.

You will control the manipulator in two different ways. In the (1) resolved-rate mode, control will be from two hand controllers located on the control station. The left controller is a translation controller and the one on the right is an attitude controller. In this mode, the end effector should be thought of as being controlled within its own axis system. The attitude of the end effector is commanded by the attitude controller in pitch, roll, and yaw. (This will be demonstrated.) In and out control motions of the translation controller cause the tip of the end effector to translate along the end effector's major axis. Side to side motions of the hand controller produce motions along the end effector axis perpendicular to the plane of the motion of its parallel jaws. Up and down motion of the translation controller causes translation of the end effector along an axis perpendicular to the plane formed by the two axes of motion previously defined.

The (2) joint-by-joint motion is inputted through the joint-by-joint controller to the right of the attitude controller. The joint to be controlled is selected by a rotary switch with positions off and 1 through 6. Positive or negative commanded motion is inputted through a toggle switch just behind the rotary selector. In this mode (for this implementation) only one joint at a time can be controlled.

The opening and closing of the jaws on the end effector is controlled by a trigger and thumb switch on the attitude controller for the resolved-rate mode. Pulling the trigger closes the jaws while pressing the thumb switch opens them. The degree of opening is proportional to the length of time the trigger is depressed and conversely for the thumb switch. In the joint-by-joint mode the end effector is controlled by the toggle switch from position number 6 on the rotary switch.

For both joint-by-joint and resolved-rate modes the gain of the commanded motion is controlled from a foot pedal located near your right foot. The end effector has constant gain and is not affected by the device. Think of foot pedal as being like an accelerator on a car (the farther down you push it, the faster the joint moves). There is no spring return on the pedal. It stays where you leave it.

Your performance of the task will be rated according to the average time you require to successfully complete the task. It will also be judged by the number of times during the task the manipulator or peg is caused to contact things in the environment which are not required to be contacted as a part of the task performance. Neither of these performance indices should be considered more important than the other.

Before data runs begin, you will be permitted several sessions to become thoroughly familiar with the task, the manipulator, and the controls. It is intended to give you sufficient practice that you will be able to perform the task so well that further practice would cause little or no improvement in your performance. We will keep a log of your practice time as well as some of your task times to help us

determine when you reach this point. However, you should also keep us apprised of when you believe yourself to be thoroughly trained.

Be advised that the PUMA manipulator is capable of rapid movements which could cause considerable damage to persons or objects it might contact. Although you will be working near the PUMA in the "direct-view" experiments, you will be in no danger of being hit by the manipulator so long as you remain on the test station. Both soft and hard mechanical stops have been implemented to disallow the PUMA from contacting any point on the control station. No such guarantee can be made if you leave the station or approach the manipulator while its high power is on. The red power-on light on the PUMA control rack (fig. B3) indicates high power is on. It will be activated only after you have taken your place on the control station. For your additional protection an observer will be on hand at all times with a remote kill button to remove power should a problem arise.

Control will be from two different locations to repeat two different task/view situations. The first runs will be made at the direct-view control station (fig. 4) from which you will be able to directly view the task board. You will be approximately 5 ft from the task board and able to see all relevant parts of it well. The scene will be viewed to your right. The second control station is located in a room some distance from the manipulator and the task board. You will view the task scene from an 8-in. black-and-white TV monitor which will present a picture derived from a TV camera located at the eye position you had at the direct-view station. The 8-in. monitor will be located directly in front of you as in figure B3. At this station, it is intended that you be isolated from any direct visual or auditory contact with the task. The exact same task variations will be repeated at both control locations. However, the direct-view runs will be completed before any are begun at the remote station.

Finally some of the task variation will require you to place a very close tolerance peg in the receptacle and others will require the insertion of a loosely fitted peg. Obviously, the tight fit will be more difficult and take longer to do. Do not worry about this, just try to get your best time while still doing the job smoothly.

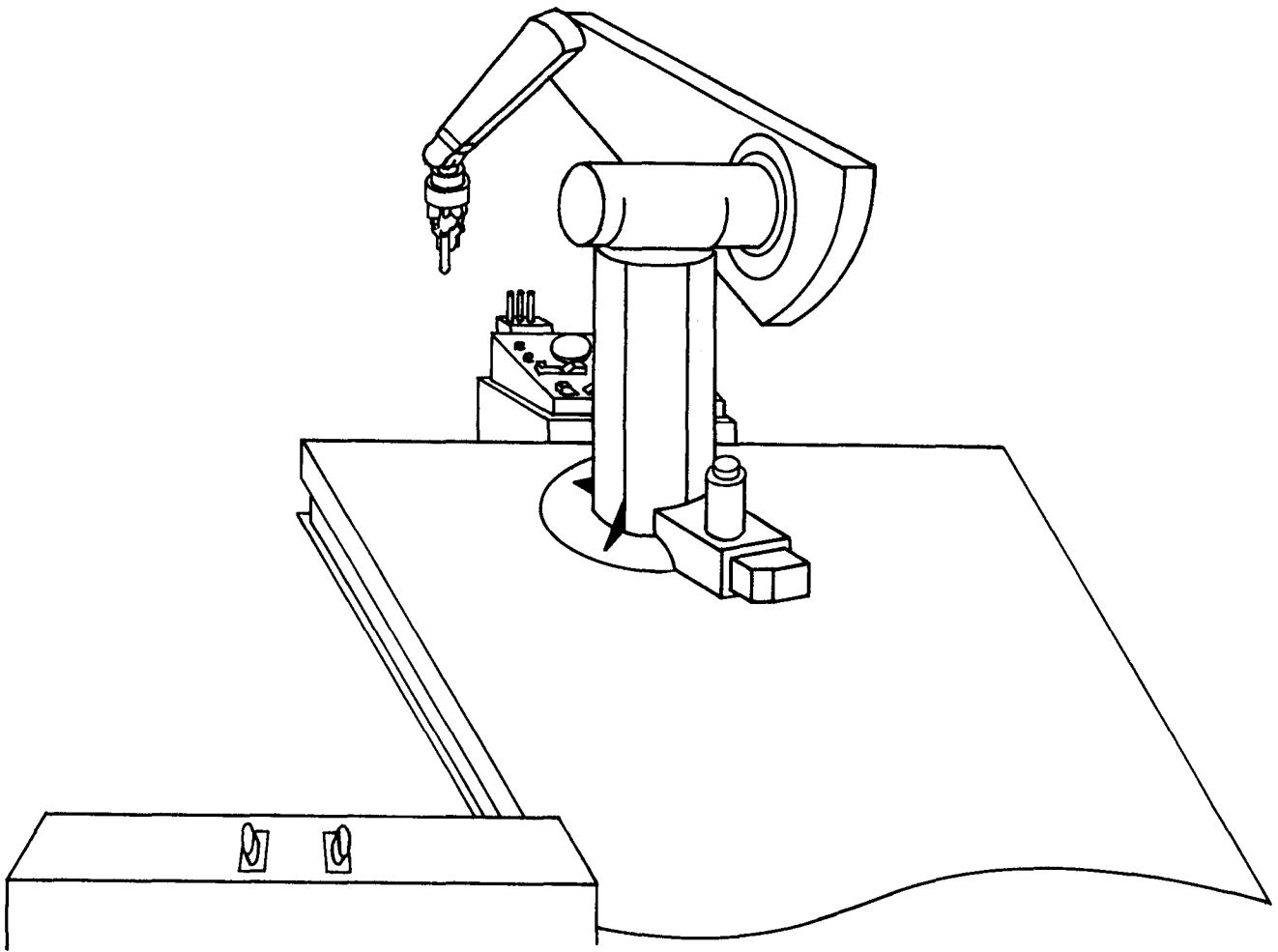


Figure B1.- Setup for experimental task.

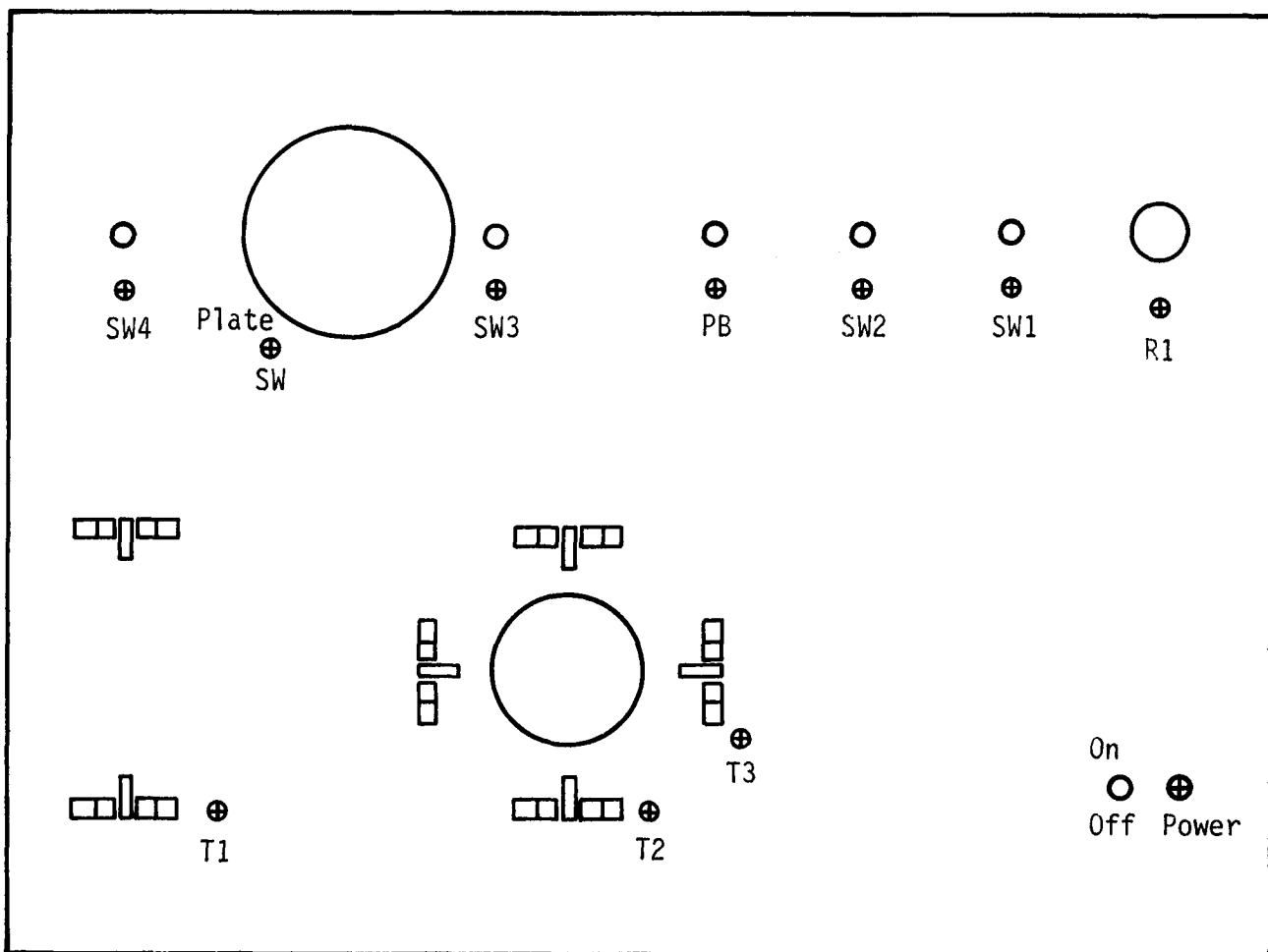


Figure B2.- Task board.



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Figure B3.- Subject at indirect-view control station.

APPENDIX C

SUBJECT COMMENTS

Subjects were asked to freely comment on their activities both during their runs and after the data acquisition was complete. They were asked to evaluate the tests in general and to comment on the available cues or lack of them, the adequacy of the lighting conditions, the angles through which they viewed the task, and so forth. A brief questionnaire presented to the subjects to stimulate their thinking and responses concerning these issues is contained in appendix D. From the responses we received, the following seem to be the most significant and noteworthy:

1. The indirect-view task differed in difficulty from the direct-view task primarily in the ease of hitting the switches. This was caused by the loss of stereoscopic vision when the TV was used. Putting the peg in the hole was about as difficult for either setup because it did not require stereoscopic vision.

2. Greater TV resolution would help the indirect-view performance, especially during insertions.

3. Both a wide TV view as well as a close-up view of the task board would enhance performance. The wide view would help in the joint-by-joint control mode, in which the subject benefits by being able to see the changing configuration of the arm. In this mode, where the end effector is and its attitude at that point are determined by the subject's configuring of the manipulator links on an individual basis. Thus, being able to see the entire manipulator arm provides useful feedback which is not required in the resolved-rate mode, in which only the end effector itself is of concern.

4. Reflection of the peg in the surface of the task board was an important alignment cue especially in the joint-by-joint mode. Controlling to bring about a tip-to-tip intersection of the peg and its reflection was a useful approach to making insertions.

5. The benefits of using gain control were greater in the joint-by-joint mode than in the resolved-rate mode.

6. The translation controller was not naturally placed to relate its control directions to corresponding movements of the manipulator. For instance, fore and aft inputs to the controller produced up and down movements of the end effector. The effect of this lack of correspondence, however, was primarily to increase learning time, not to reduce ultimate performance. Possibly a more natural or comfortable location for the resolved-rate controllers would be on the ends of the arm rests of the subject's seat.

7. Insufficient cues to detect slippage of the peg in the end-effector jaws were a problem during both insertions and extractions.

8. Training was adequate. (This was a unanimous expression of the subjects.)

9. Lighting was generally adequate, but additional lighting might have provided additional detail around the edges of the opening of the receptacle, which could have facilitated the insertion task.

10. Joint-by-joint control was the most difficult control mode. The 0.995-in. peg was the most difficult peg size. The two together in combination were the most difficult task.

11. The viewing angle was generally good, although some cues were missing. There is probably no other single viewing angle which would not result in subtle visual cues being missed. Two orthogonal TV camera views or stereo TV would have provided much more information.

12. Force and torque information would be useful in making insertions and extractions of the peg.

APPENDIX D

QUESTIONNAIRE FOR SUBJECTS

The following questionnaire was presented to the subjects upon completion of the experiment to elicit from them comments on the various aspects of their participation.

We are interested in putting in our report on the teleoperator studies in which you participated during the first half of 1984 a section on Subject Comments. That is, we would like to know how you felt about the experiments in terms of task difficulty, available cues or lack of them, lighting, etc. We have gotten some comments from Jim Wise (from whom we would welcome others he might care to add), but primarily we are looking for the observations and opinions of the rest of you. To give some possible stimulation to your thoughts, we have included with this a list of relevant questions. It is not necessary that you answer these, nor should you limit your response to them. Just give us what you will. Thanks!

1. What parts of the task were the most difficult? Which were the easiest?
2. Did you need more training?
3. Was lighting adequate? How would you change it?
4. Was the viewing angle good? What was wrong with it?
5. Did you like the hand controllers? Were they well and naturally placed? Where would you like to place them? Careful now!
6. Was the TV placement OK? Was the resolution good? What would you change?
7. What visual information was not adequate? What cues were missing? How did you compensate?

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TABLE 1.- TEST MATRIX

Run	View		Peg size, in.		Control mode	
	Direct	Indirect	0.995	0.500	Joint by joint	Resolved rate
1	x		x		x	
2	x		x			x
3	x			x	x	
4	x			x		x
5		x	x		x	
6		x	x			x
7		x		x	x	
8		x		x		x

TABLE 2.- ACCUMULATED TIME ON SYSTEM FOR EACH SUBJECT

Subject	Direct-view training, minutes	Indirect-view training, minutes
1	697	331
2	535	444
3	450	240
4	458	348

TABLE 3.- RAW DATA OF TASK COMPLETION TIMES

(a) Direct-view setup

Subject	Code (a)	Task completion times, sec, for replication no. -										Mean, sec	Standard deviation, sec
		1	2	3	4	5	6	7	8	9	10		
1	1	68.9	80.1	90.5	79.0	63.8	71.1	82.1	58.3	70.1	83.3	74.72	9.39
	3	158.2	129.5	199.1	91.7	111.5	143.5	125.4	88.0	103.6	121.6	127.21	31.68
	7	263.6	204.6	177.1	194.5	192.6	201.7	160.3	150.2	207.4	179.9	193.19	29.55
	9	304.0	270.1	365.7	257.7	234.3	289.0	240.8	235.6	225.1	274.9	269.72	40.22
2	1	103.1	88.8	99.5	75.6	85.2	88.6	144.8	104.3	110.1	87.0	98.70	18.33
	3	382.5	139.4	163.5	179.0	156.3	180.3	226.8	196.2	245.4	214.5	208.39	65.84
	7	236.3	232.6	250.4	245.6	201.5	205.3	181.9	199.8	215.8	198.2	216.74	21.93
	9	520.2	344.4	418.9	454.5	360.4	471.1	518.1	515.8	304.4	383.6	429.14	74.68
3	1	128.3	126.9	102.5	139.1	129.6	130.2	109.8	98.4	101.8	91.7	115.83	15.85
	3	410.5	226.8	199.6	163.5	146.3	148.3	222.5	137.0	153.0	199.3	200.68	76.55
	7	383.7	377.8	269.3	258.9	224.2	216.6	213.4	192.6	208.5	177.9	252.29	69.24
	9	498.7	631.0	337.5	526.1	313.3	305.5	409.1	264.7	277.7	319.7	388.33	117.38
4	1	80.5	90.4	89.2	80.6	67.7	85.8	95.3	66.3	83.3	80.3	81.94	8.79
	3	99.1	143.8	237.2	129.5	111.1	153.1	150.7	163.6	155.2	108.4	145.17	37.26
	7	291.6	316.6	279.6	247.9	249.4	287.8	285.3	254.2	246.8	272.9	273.21	22.11
	9	486.1	508.7	508.0	487.6	479.5	571.4	409.7	431.9	436.3	416.8	473.60	47.76

^a₁ - 0.500-in. peg, resolved rate; 3 - 0.995-in. peg, resolved rate; 7 - 0.500-in. peg, joint by joint; 9 - 0.995-in. peg, joint by joint.

TABLE 3.- Concluded

(b) Indirect-view setup

Subject	Code (a)	Task completion times, sec, for replication no. -										Mean, sec	Standard deviation, sec
		1	2	3	4	5	6	7	8	9	10		
1	4	81.5	96.5	98.8	102.1	80.3	80.4	85.3	102.5	78.2	68.1	87.37	11.19
	6	121.7	110.8	89.6	108.5	169.9	130.5	207.4	98.4	85.3	113.1	123.52	36.02
	10	186.0	189.4	248.7	160.1	192.1	167.6	201.1	182.6	177.4	189.5	189.45	22.80
	12	225.5	273.2	208.7	279.9	224.8	193.1	241.7	234.3	274.3	232.6	238.81	27.51
2	4	85.5	109.2	99.8	100.7	95.2	102.3	90.1	75.8	81.3	74.6	91.45	11.27
	6	182.9	179.1	170.4	204.3	194.7	180.3	157.2	129.4	167.0	144.0	170.93	21.52
	10	251.8	197.6	230.5	232.9	217.6	217.3	183.1	217.5	202.1	183.2	213.36	20.99
	12	283.4	342.8	405.7	401.0	399.3	342.8	369.1	276.9	399.8	294.0	351.48	48.97
3	4	129.5	125.8	101.1	102.9	95.1	124.0	95.4	108.5	150.8	83.4	111.65	19.33
	6	215.7	194.5	208.4	123.6	239.9	164.8	141.2	139.3	222.9	208.8	185.91	38.44
	10	254.8	201.3	239.8	198.6	234.1	242.2	182.9	253.7	209.1	209.2	222.57	24.05
	12	389.8	358.3	355.6	330.2	317.2	276.1	344.4	361.1	456.7	448.8	363.82	52.92
4	4	151.6	108.2	98.5	81.8	129.0	98.2	125.2	116.3	105.2	90.5	110.45	19.58
	6	147.9	166.1	173.7	191.0	147.7	143.5	204.8	125.4	185.0	161.7	164.68	23.17
	10	401.3	296.1	279.4	232.9	335.9	286.9	279.5	335.1	242.2	233.6	292.29	50.47
	12	593.9	563.8	565.7	350.1	402.9	479.8	403.5	439.4	450.3	454.6	470.40	76.33

^a4 - 0.500-in. peg, resolved rate; 6 - 0.995-in. peg, resolved rate; 10 - 0.500-in., joint by joint; 12 - 0.995-in. peg, joint by joint.

TABLE 4.- RAW DATA OF NUMBER OF IMPACTS

(a) Direct-view setup

Subject	Code (a)	Number of impacts for replication no. -										Mean, sec	Standard deviation, sec
		1	2	3	4	5	6	7	8	9	10		
1	1	0	1	3	1	0	0	0	0	1	0	0.60	0.92
	3	6	4	5	2	3	4	2	2	1	3	3.20	1.47
	7	3	4	3	1	2	0	2	0	3	0	1.80	1.40
	9	0	7	4	4	3	3	1	5	1	5	3.30	2.05
2	1	0	0	0	0	0	0	0	0	1	0	1.10	0.30
	3	10	3	2	0	2	1	0	0	0	0	1.80	2.93
	7	0	2	0	0	0	0	0	0	0	0	.20	.60
	9	2	0	2	2	2	2	2	4	0	0	1.60	1.20
3	1	0	0	0	2	0	1	0	0	0	0	0.30	0.64
	3	6	0	2	0	1	1	1	2	1	1	1.50	1.63
	7	3	3	0	0	1	1	0	0	0	0	.80	1.17
	9	0	2	0	2	1	1	1	2	2	2	1.30	.78
4	1	0	0	0	0	0	0	0	0	1	2	0.30	0.64
	3	2	3	2	1	2	1	0	0	2	0	1.30	1.00
	7	0	3	0	2	1	1	2	1	0	0	1.00	1.00
	9	2	3	1	2	4	1	2	1	0	3	1.90	1.14

^a₁ - 0.500-in. peg, resolved rate; 3 - 0.995-in. peg, resolved rate;
7 - 0.500-in. peg, joint by joint; 9 - 0.995-in. peg, joint by joint.

TABLE 4.- Concluded

(b) Indirect-view setup

Subject	Code (a)	Number of impacts for replication no. -										Mean, sec	Standard deviation, sec
		1	2	3	4	5	6	7	8	9	10		
1	4	1	0	1	3	0	1	0	1	1	0	0.80	0.87
	6	4	1	1	0	4	1	5	2	1	2	2.10	1.58
	10	1	0	2	2	1	0	2	0	1	1	1.00	.77
	12	3	2	2	2	2	2	2	1	2	4	2.20	.75
2	4	0	0	1	0	0	0	0	0	0	0	0.10	0.30
	6	2	2	0	1	0	0	1	0	1	1	.80	.75
	10	1	0	1	0	0	1	0	1	2	0	.60	.66
	12	2	2	0	1	1	0	1	0	2	0	.90	.83
3	4	0	0	1	0	0	0	0	0	1	0	0.20	0.40
	6	0	2	0	2	1	1	1	2	2	2	1.30	.78
	10	2	0	2	2	1	1	1	2	2	2	1.50	.67
	12	1	1	0	2	2	3	2	1	2	2	1.60	.80
4	4	0	2	0	0	2	1	2	0	0	0	0.70	0.90
	6	0	1	1	1	1	0	3	2	0	1	1.00	.89
	10	2	0	1	1	2	1	3	3	2	1	1.60	.92
	12	0	0	0	1	4	1	1	1	2	2	1.20	1.17

^a4 - 0.500-in. peg, resolved rate; 6 - 0.995-in. peg, resolved rate;
10 - 0.500-in., joint by joint; 12 - 0.995-in. peg, joint by joint.

TABLE 5.- ANALYSIS OF VARIANCE COMPARISON OF LaRC DATA WITH GRUMMAN DATA

[0.500-in. peg; resolved-rate control]

Performance measure	View	LaRC mean	Grumman mean	F-ratio	Degrees of freedom		F-ratio ^a for significance at 99%
					Numerator	Denominator	
Task completion time	Direct	92.80	69.03	32.46	1	39	7.33
	Indirect	100.23	77.21	32.80	1	39	7.33
No. of impacts	Direct	.33	2.40	58.58	1	39	7.33
	Indirect	.45	3.20	80.88	1	39	7.33

^aThe F-ratio must be larger than the number in this column to be significant at the specified confidence level.

TABLE 6.- ANALYSIS OF VARIANCE FOR TASK COMPLETION TIME FOR DIRECT-VIEW SETUP

Variable	F-ratio	Degrees of freedom		F-ratio ^a for significance at 99%
		Numerator	Denominator	
Subjects	17.87	3	135	3.94
Peg size	177.25	1	135	6.84
Subjects and peg size	16.05	3	135	3.94
Control mode	421.95	1	135	6.84
Subjects and control mode	30.00	3	135	3.94
Peg size and control mode	20.11	1	135	6.84
Subjects, peg size, and control mode	6.26	3	135	3.94

^aThe F-ratio must be larger than the number in this column to be significant at the specified confidence level.

TABLE 7.- ANALYSIS OF VARIANCE FOR NUMBER OF IMPACTS
FOR DIRECT-VIEW SETUP

Variable	F-ratio	Degrees of freedom		F-ratio ^a for significance at 99%
		Numerator	Denominator	
Subjects	8.84	3	135	3.94
Peg size	37.14	1	135	6.84
Subjects and peg size	2.14	3	135	3.94
Control mode	1.97	1	135	6.84
Subjects and control mode	.90	3	135	3.94
Peg size and control mode	2.32	1	135	6.84
Subjects, peg size, and control mode	.37	3	135	3.94

^aThe F-ratio must be larger than the number in this column to be significant at the specified confidence level.

TABLE 8.- ANALYSIS OF VARIANCE FOR TASK COMPLETION TIME
FOR THREE SUBJECTS

[Direct-view setup]

Variable	F-ratio	Degrees of freedom		F-ratio ^a for significance at 99%
		Numerator	Denominator	
Subjects	0.08	2	99	4.88
Peg size	138.32	1	99	6.96
Subjects and peg size	1.64	2	99	4.88
Control mode	297.34	1	99	6.96
Subjects and control mode	7.57	2	99	4.88
Peg size and control mode	18.01	1	99	6.96
Subjects, peg size, and control mode	1.19	2	99	4.88

^aThe F-ratio must be larger than the number in this column to be significant at the specified confidence level.

TABLE 9.- ANALYSIS OF VARIANCE FOR NUMBER OF IMPACTS
FOR THREE SUBJECTS

[Direct-view setup]

Variable	F-ratio	Degrees of freedom		F-ratio ^a for significance at 99%
		Numerator	Denominator	
Subjects	0.41	2	99	4.88
Peg size	19.83	1	99	6.96
Subjects and peg size	1.25	2	99	4.88
Control mode	.06	1	99	6.96
Subjects and control mode	.97	2	99	4.88
Peg size and control mode	1.13	1	99	6.96
Subjects, peg size, and control mode	.42	2	99	4.88

^aThe F-ratio must be larger than the number in this column to be significant at the specified confidence level.

TABLE 10.- ANALYSIS OF VARIANCE FOR TASK COMPLETION TIME
FOR INDIRECT-VIEW SETUP

Variable	F-ratio	Degrees of freedom		F-ratio ^a for significance at 99%
		Numerator	Denominator	
Subjects	48.92	3	135	3.94
Peg size	254.35	1	135	6.84
Subjects and peg size	8.48	3	135	3.94
Control mode	757.65	1	135	6.84
Subjects and control mode	23.94	3	135	3.94
Peg size and control mode	31.12	1	135	6.84
Subjects, peg size, and control mode	3.72	3	135	3.94

^aThe F-ratio must be larger than the number in this column to be significant at the specified confidence level.

TABLE 11.- ANALYSIS OF VARIANCE FOR NUMBER OF IMPACTS
FOR INDIRECT-VIEW SETUP

Variable	F-ratio	Degrees of freedom		F-ratio ^a for significance at 99%
		Numerator	Denominator	
Subjects	6.66	3	135	3.94
Peg size	16.71	1	135	6.84
Subjects and peg size	3.34	3	135	3.94
Control mode	8.38	1	135	6.84
Subjects and control mode	.71	3	135	3.94
Peg size and control mode	2.90	1	135	6.84
Subjects, peg size, and control mode	.29	3	135	3.94

^aThe F-ratio must be larger than the number in this column to be significant at the specified confidence level.

TABLE 12.- ANALYSIS OF VARIANCE FOR TASK COMPLETION TIME
FOR DIRECT- AND INDIRECT-VIEW SETUPS

Variable	F-ratio	Degrees of freedom		F-ratio ^a for significance at 99%
		Numerator	Denominator	
Subjects	51.06	3	279	3.88
Peg size	393.09	1	279	6.85
Subjects and peg size	11.29	3	279	3.88
Control mode	1032.01	1	279	6.85
Subjects and control mode	28.43	3	279	3.88
Peg size and control mode	46.43	1	279	6.85
Subjects, peg size, and control mode	4.68	3	279	3.88
View	3.44	1	279	6.85
Subjects and view	3.59	3	279	3.88
Peg size and view	4.84	1	279	6.85
Subjects, peg size, and view	.97	3	279	3.88
Control mode and view	2.88	1	279	6.85
Subjects, control mode, and view	.01	3	279	3.88
Peg size, control mode, and view	.42	1	279	6.85
Subjects, peg size, control mode, and view	.33	3	279	3.88

^aThe F-ratio must be larger than the number in this column to be significant at the specified confidence level.

TABLE 13.- ANALYSIS OF VARIANCE FOR NUMBER OF IMPACTS
FOR DIRECT- AND INDIRECT-VIEW SETUPS

Variable	F-ratio	Degrees of freedom		F-ratio ^a for significance at 99%
		Numerator	Denominator	
Subjects	13.36	3	279	3.88
Peg size	51.22	1	279	6.85
Subjects and peg size	4.13	3	279	3.88
Control mode	8.20	1	279	6.85
Subjects and control mode	.55	3	279	3.88
Peg size and control mode	5.25	1	279	6.85
Subjects, peg size, and control mode	.37	3	279	3.88
View	2.05	1	279	6.85
Subjects and view	2.58	3	279	3.88
Peg size and view	7.66	1	279	6.85
Subjects, peg size, and view	.78	3	279	3.88
Control mode and view	.33	1	279	6.85
Subjects, control mode, and view	1.23	3	279	3.88
Peg size, control mode, and view	.04	1	279	6.85
Subjects, peg size, control mode, and view	.41	3	279	3.88

^aThe F-ratio must be larger than the number in this column to be significant at the specified confidence level.

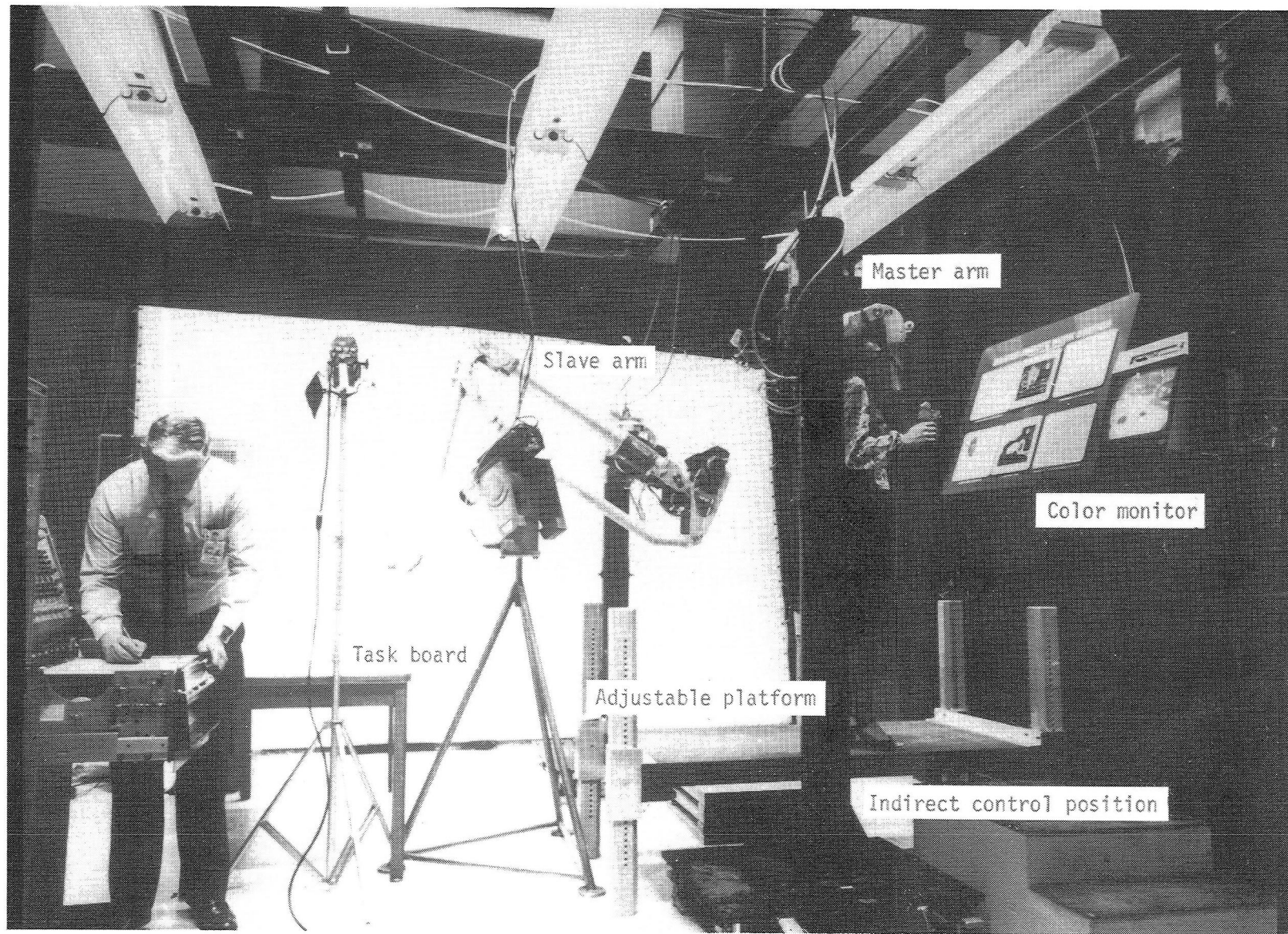


Figure 1.- Grumman Dexterous Manipulator Lab.

L-86-303

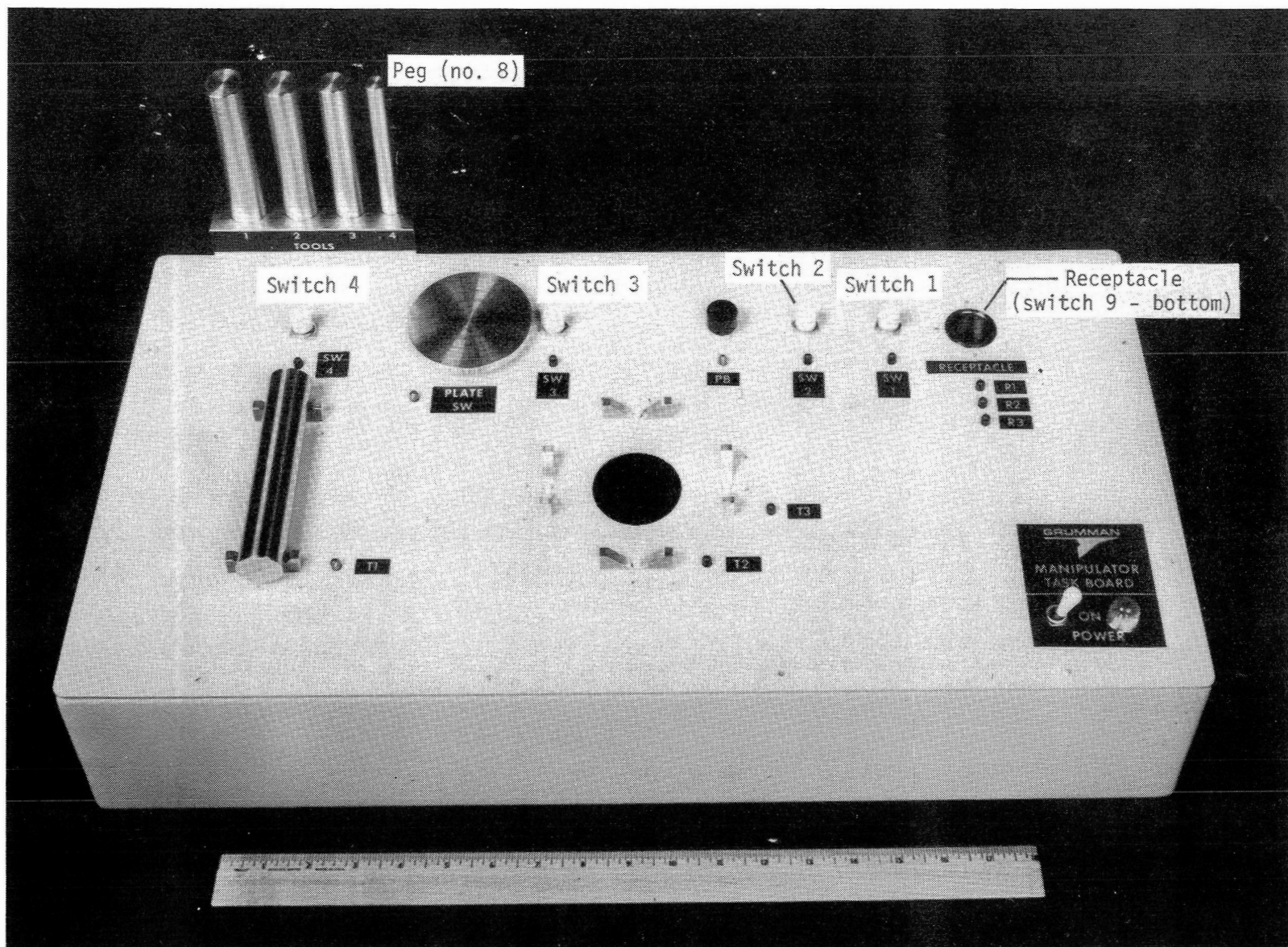


Figure 2.- Grumman task board.

L-83-3749

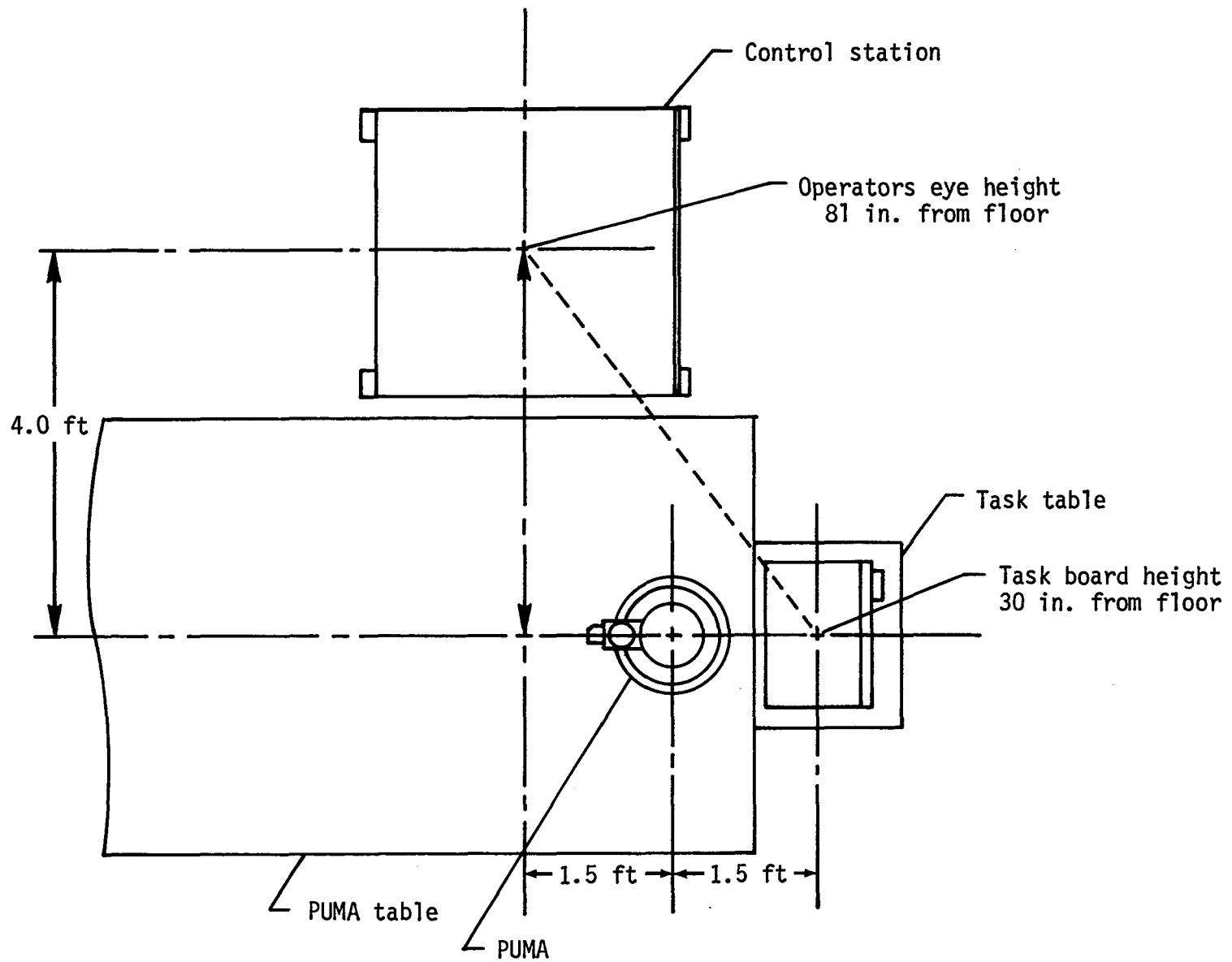
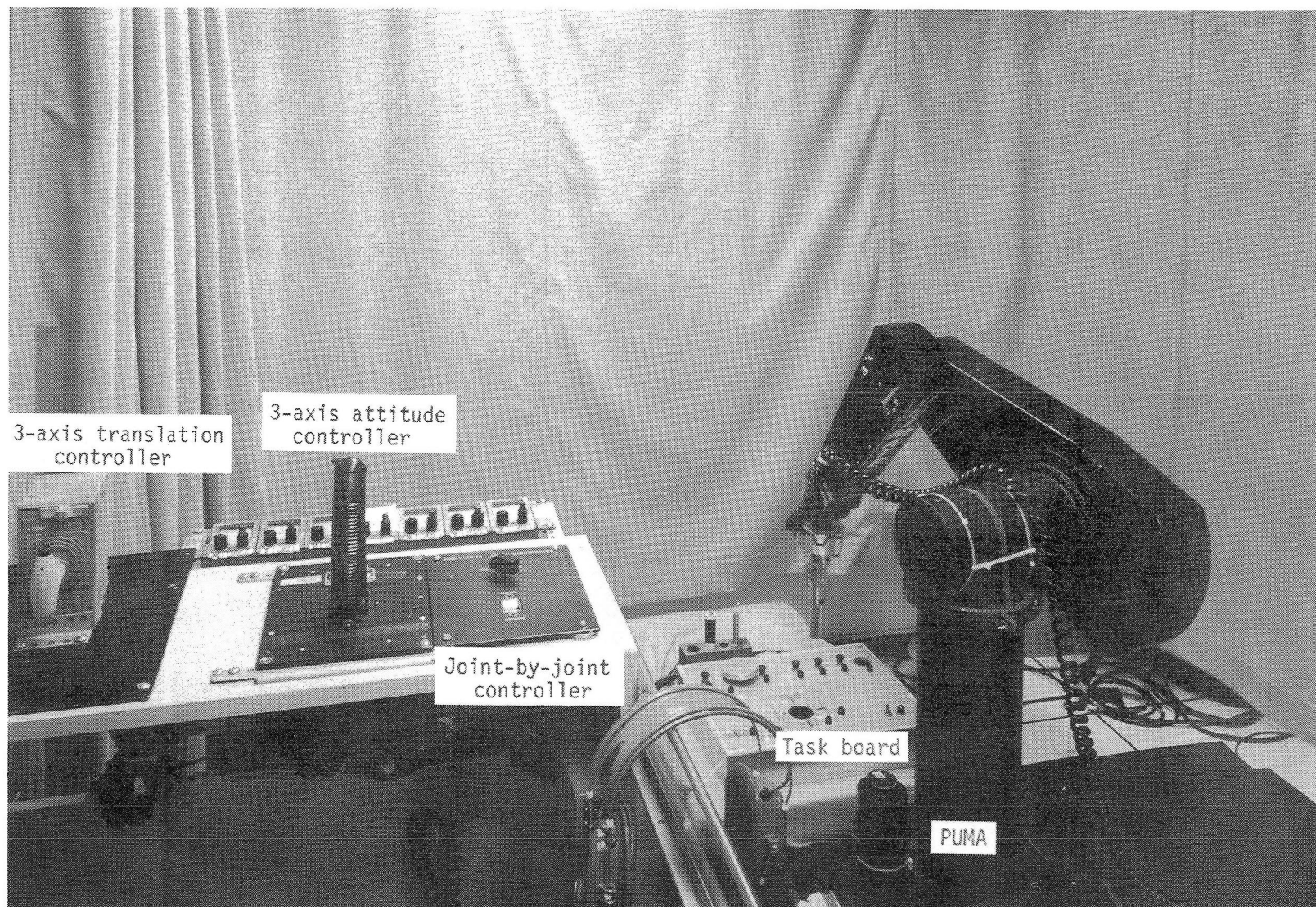


Figure 3.- Placement of equipment for direct-view test.



L-84-1198

Figure 4.- Subject controlling manipulator (direct view).



L-84-1197

Figure 5.- Direct-view control station with placement of hand controllers shown.

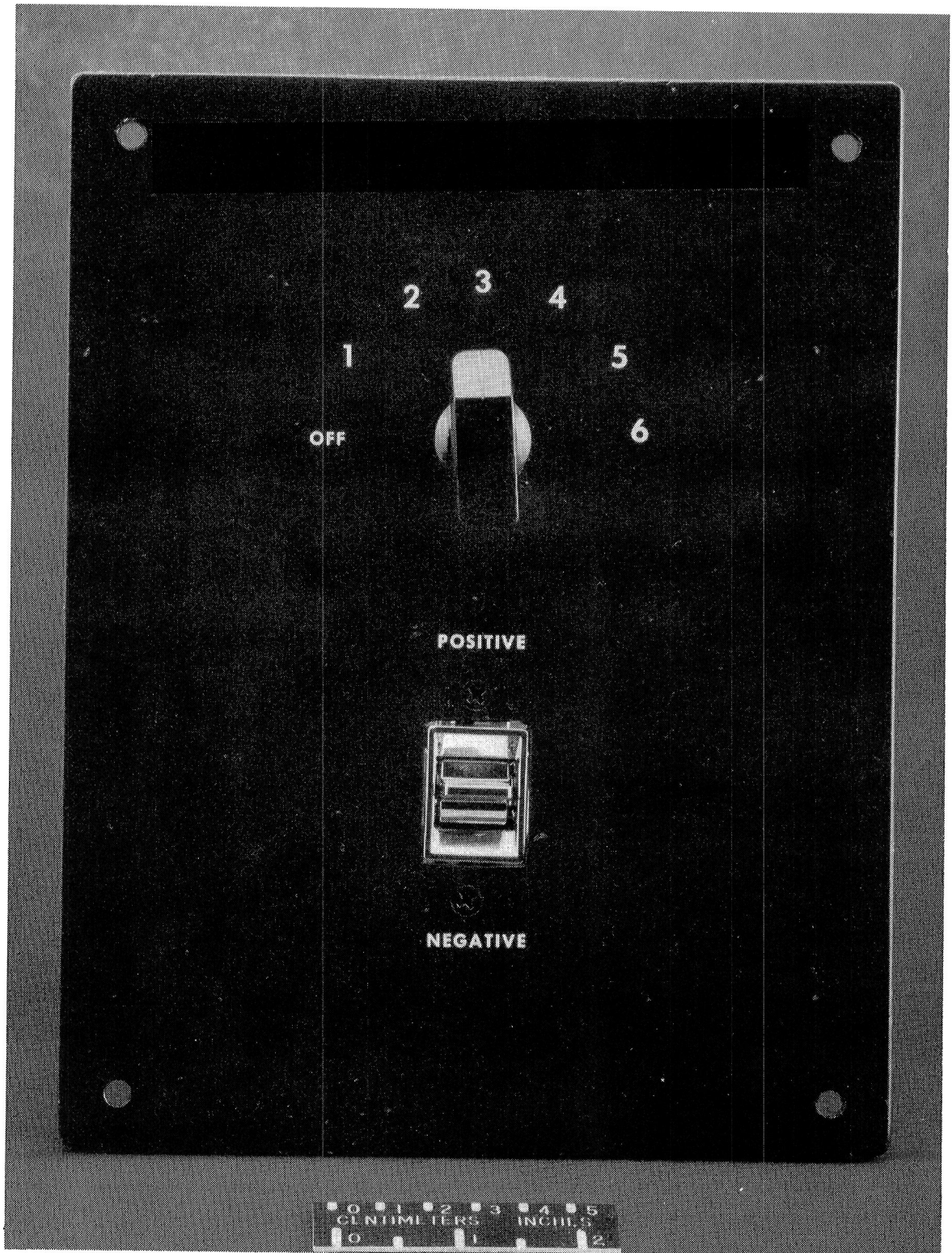


Figure 6.- Joint-by-joint controller.

L-84-5200

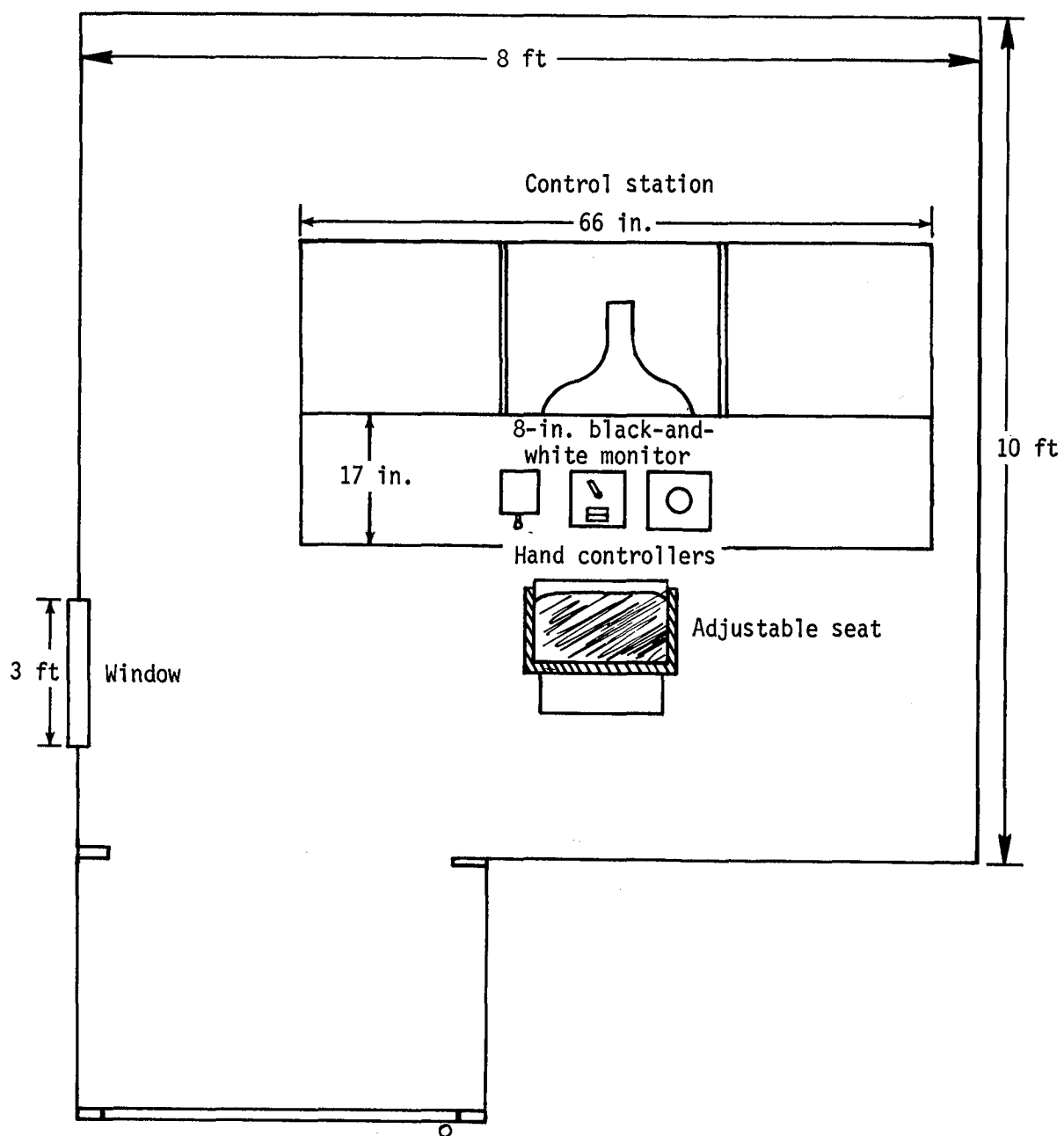


Figure 7.- Control room layout.

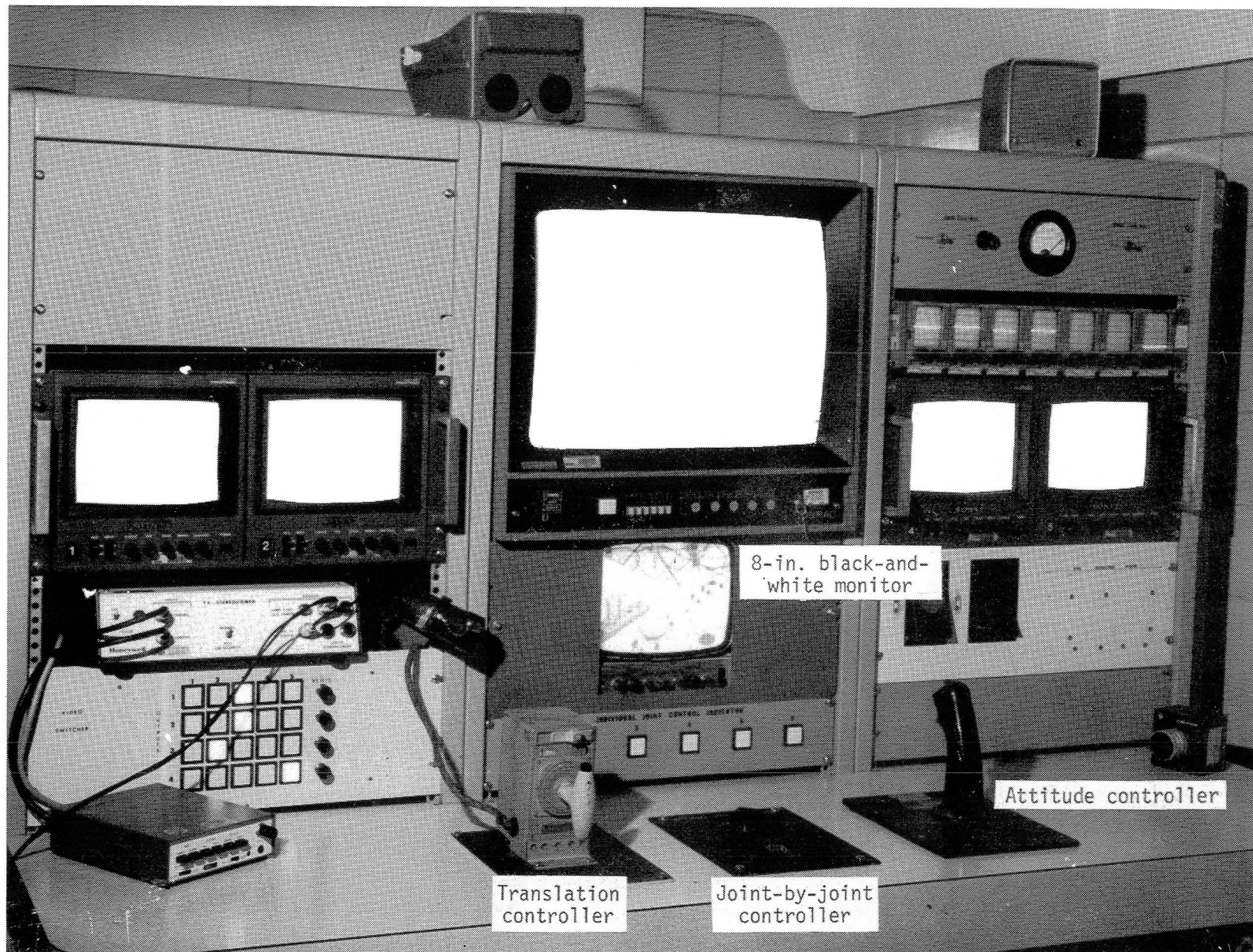


Figure 8.- Control station for indirect-view tests.

L-84-5132

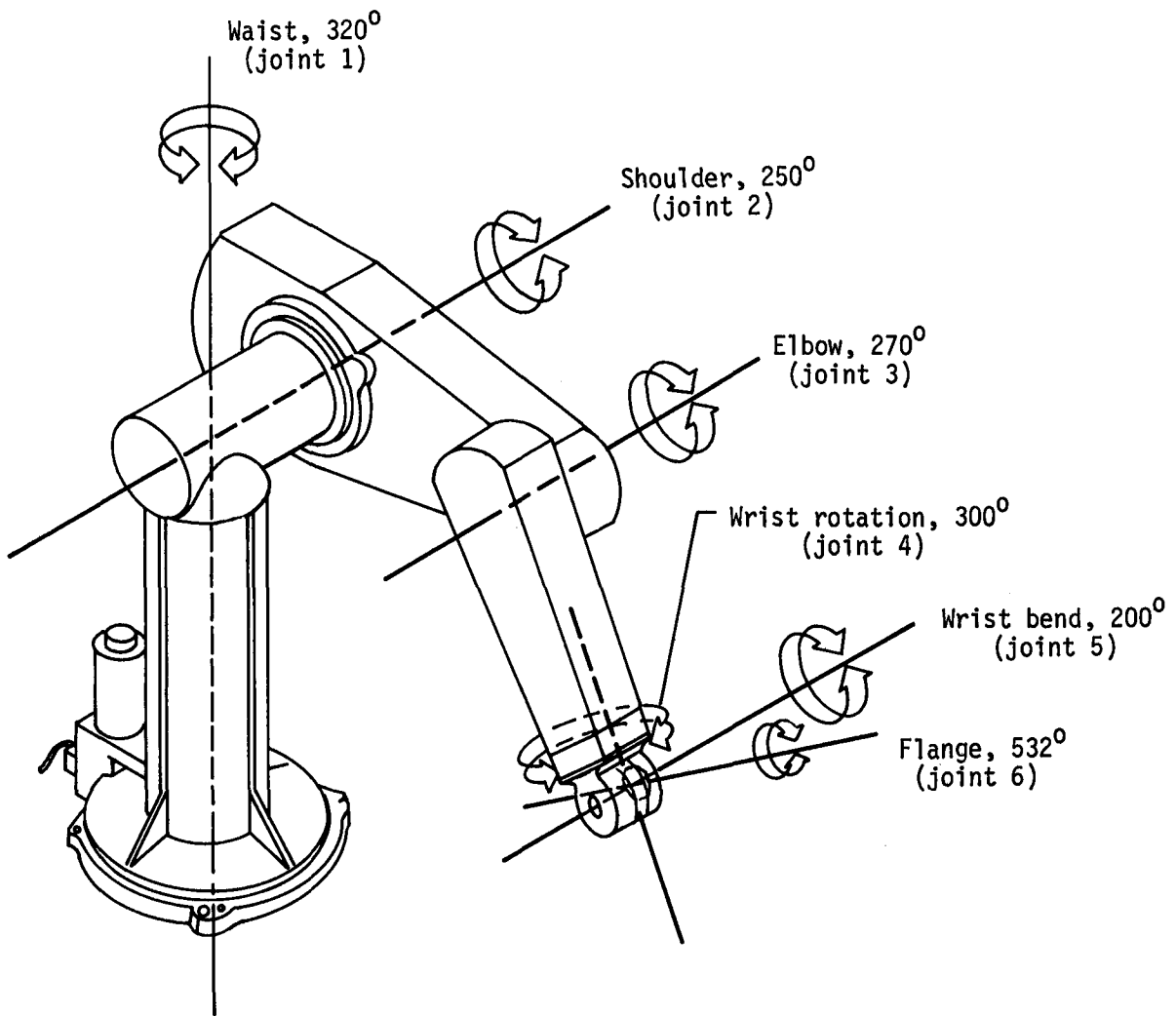
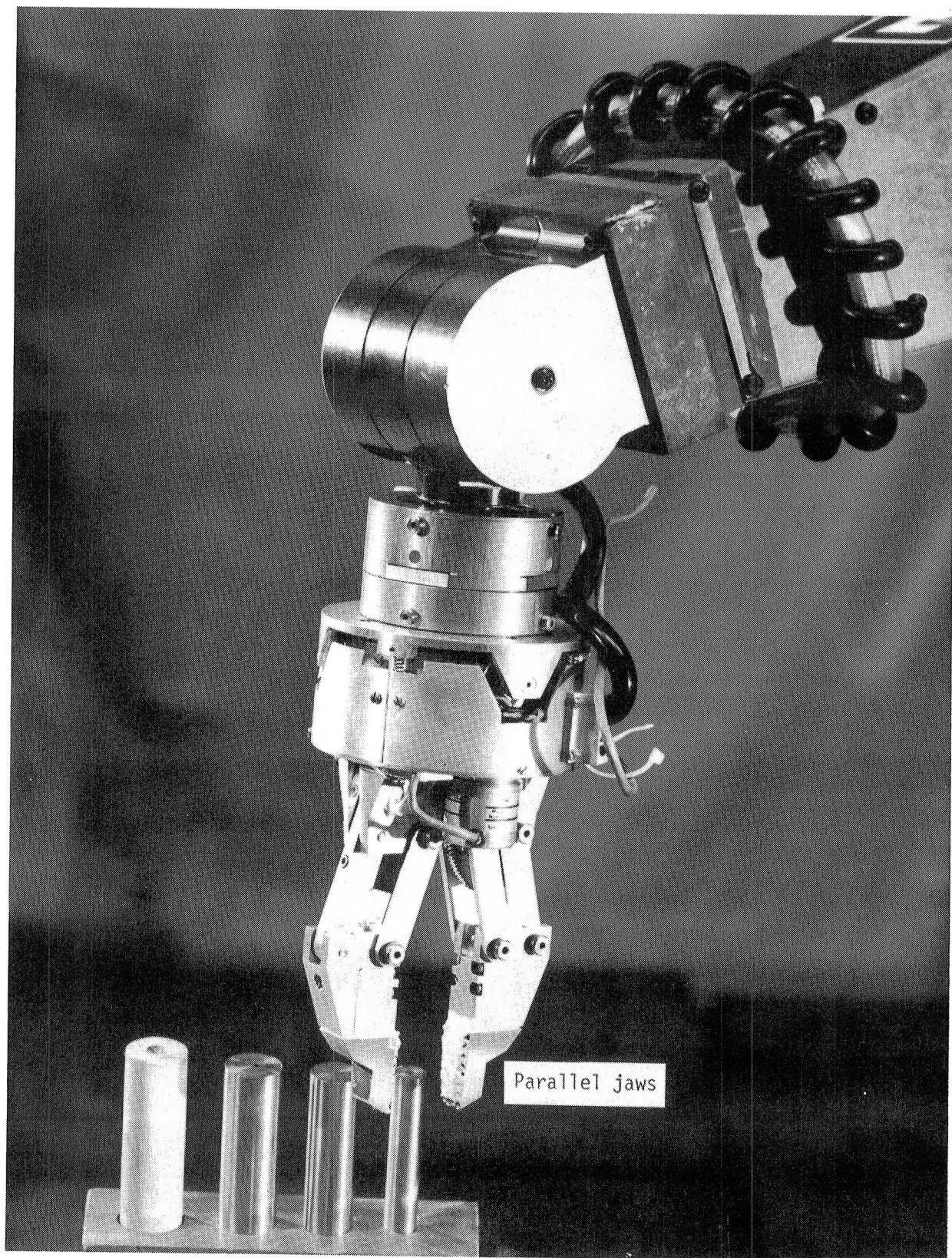
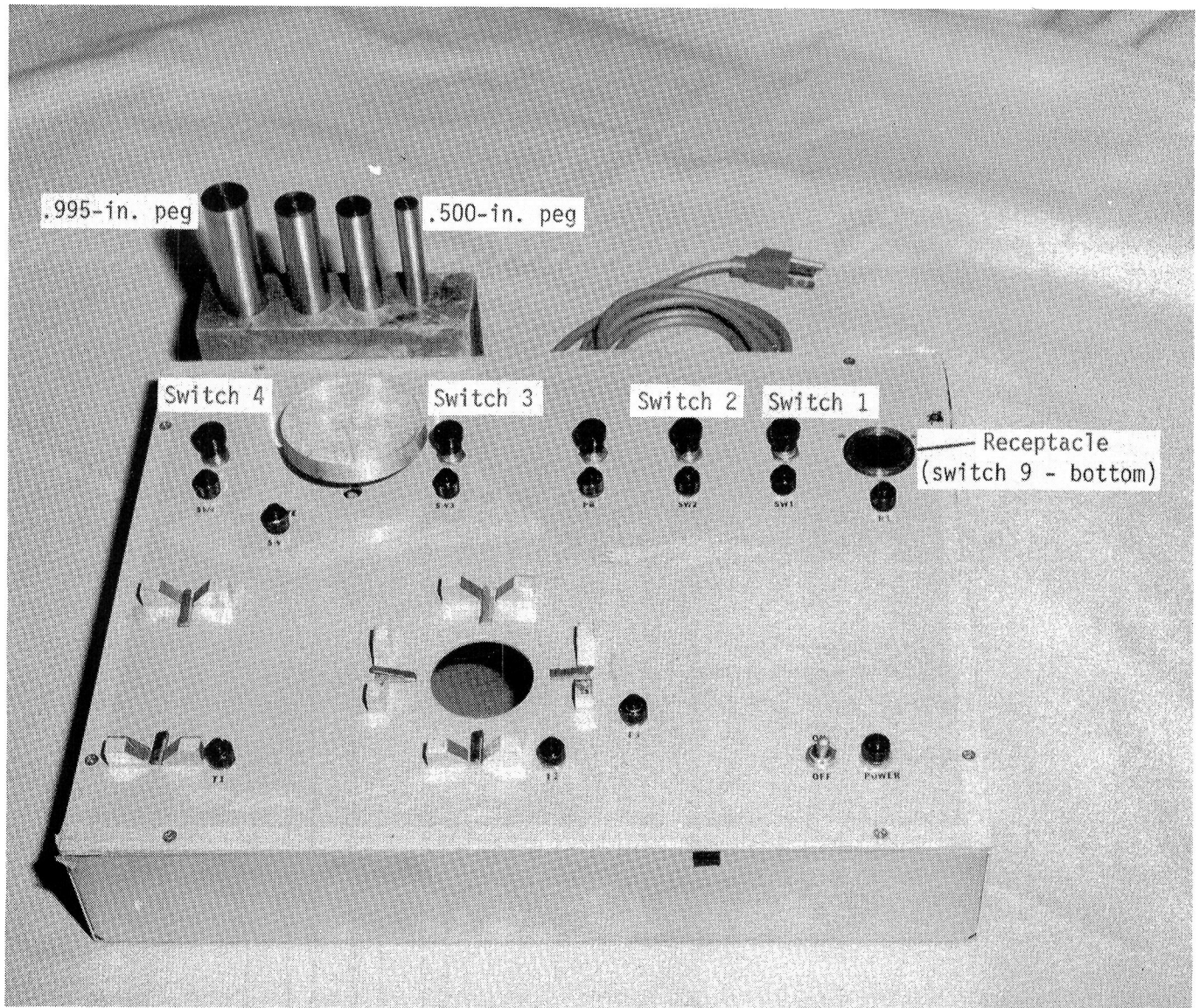


Figure 9.- PUMA member identification. Numerical values give range of motion.



L-83-8083

Figure 10.- End effector of PUMA.



L-85-1026

Figure 11.- LaRC task board.

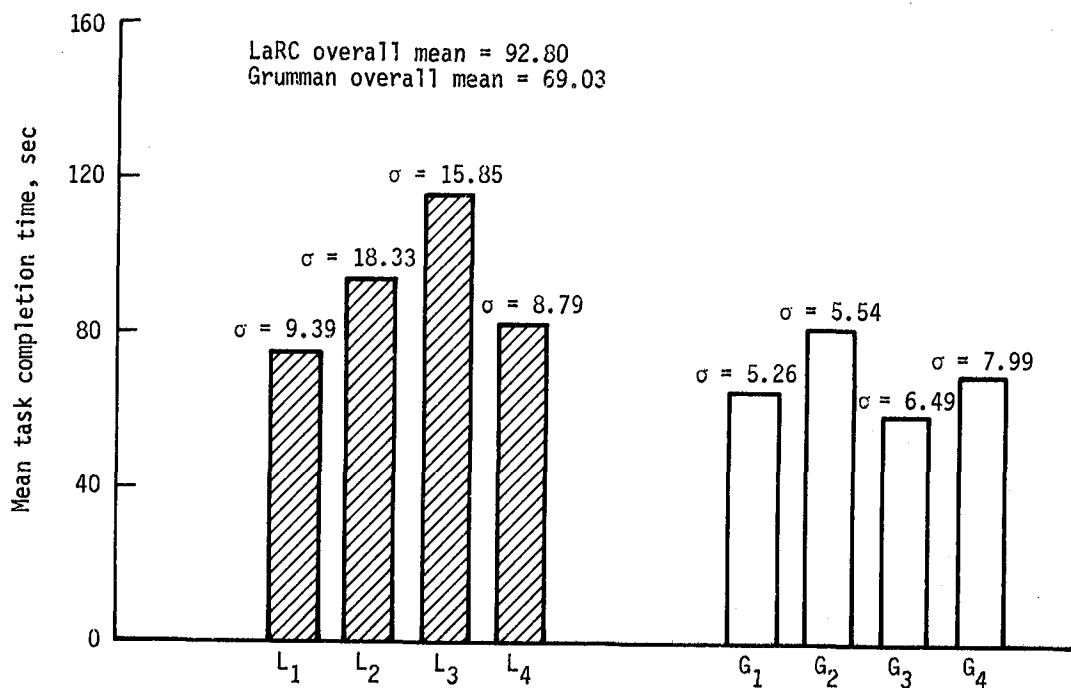


Figure 12.- Task completion times for direct-view tests with 0.500-in. peg and resolved-rate control.

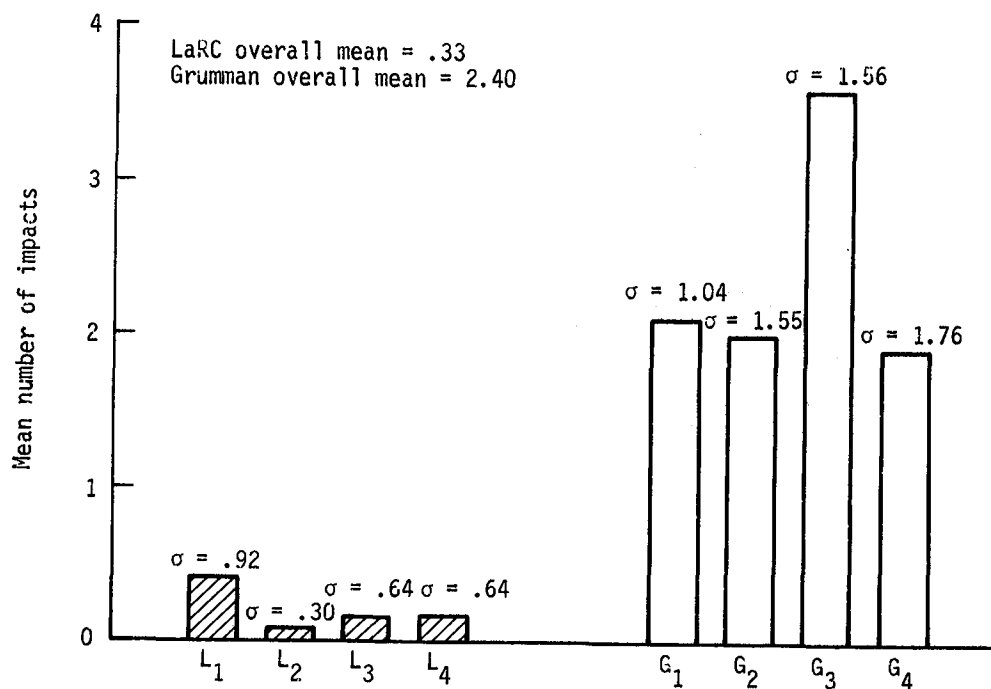


Figure 13.- Number of impacts for direct-view tests with 0.500-in. peg and resolved-rate control.

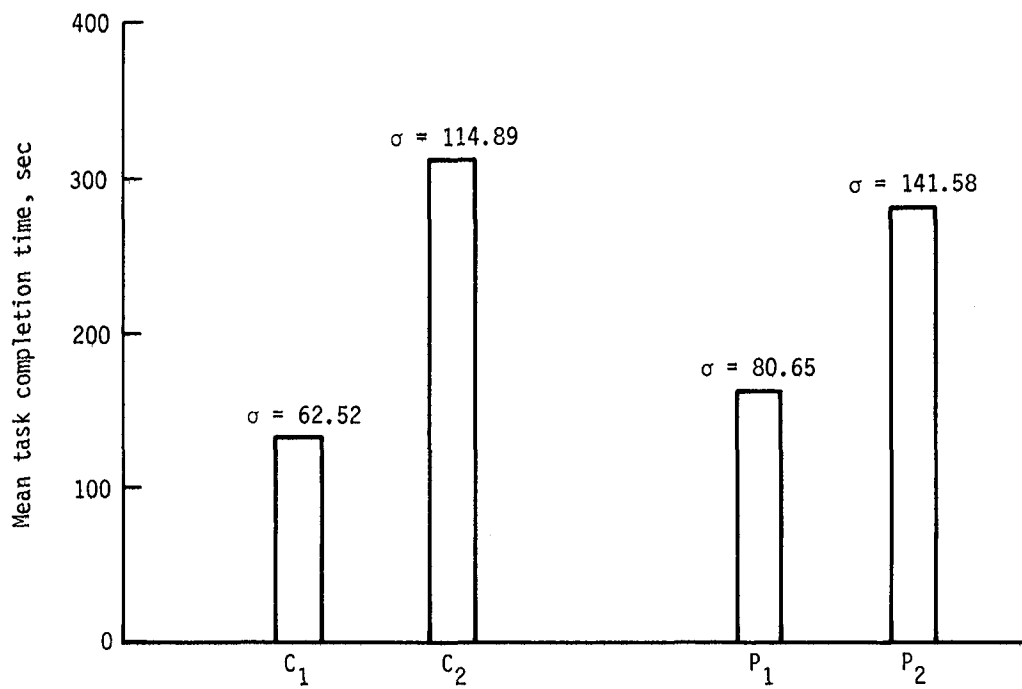


Figure 14.- Effect of control mode and peg size on task completion times for direct-view setup.

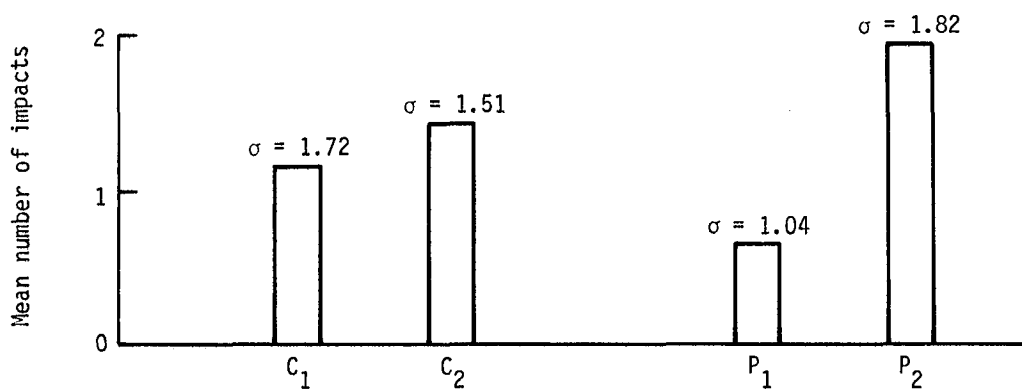


Figure 15.- Effect of control mode and peg size on number of impacts for direct-view setup.

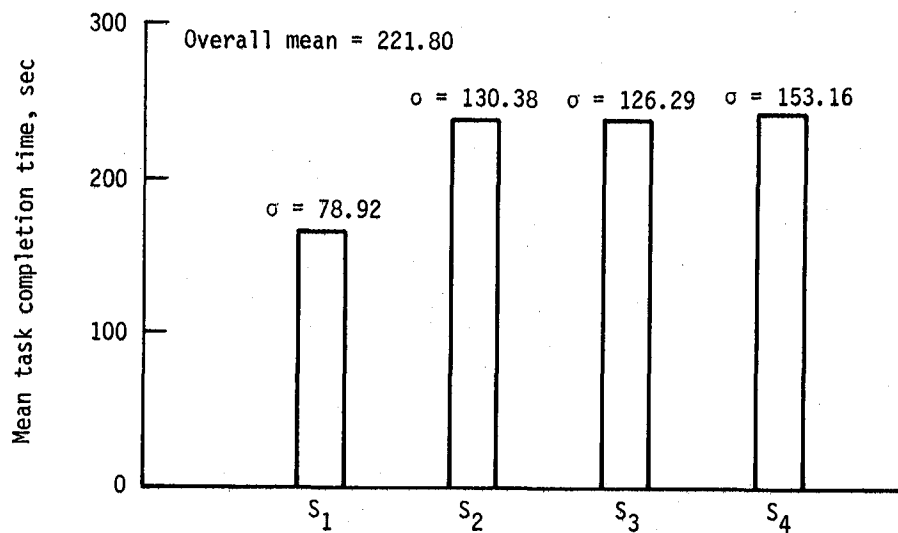


Figure 16.- Task completion times for direct-view tests with all variables considered.

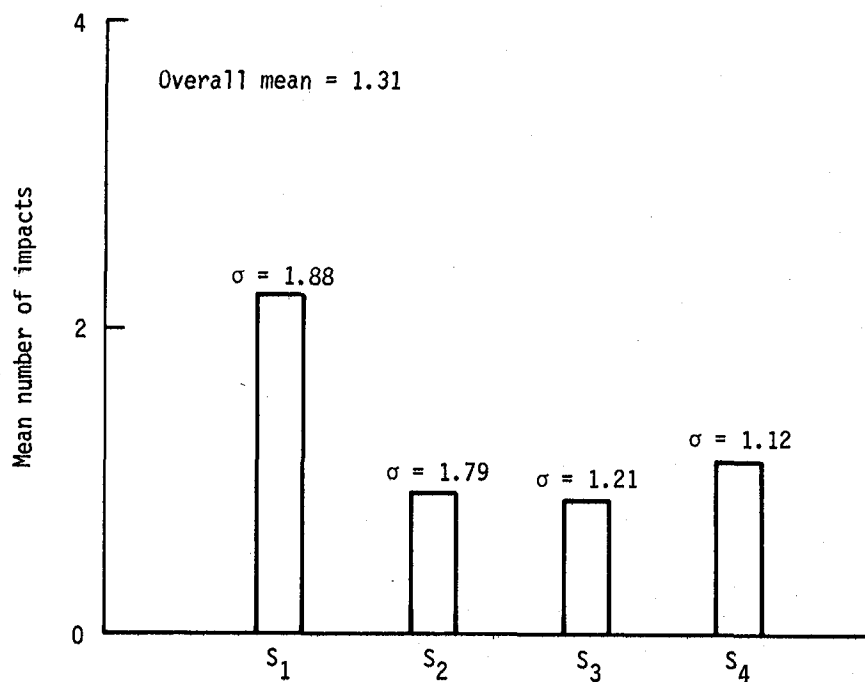


Figure 17.- Number of impacts for direct-view tests with all variables considered.

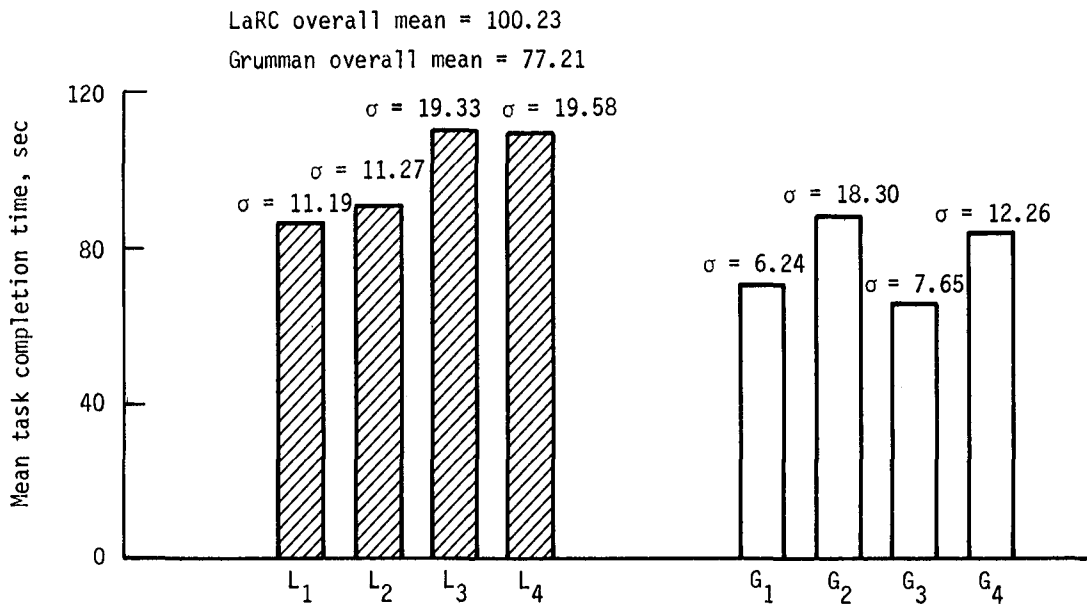


Figure 18.- Task completion times for indirect-view tests with 0.500-in. peg and resolved-rate control.

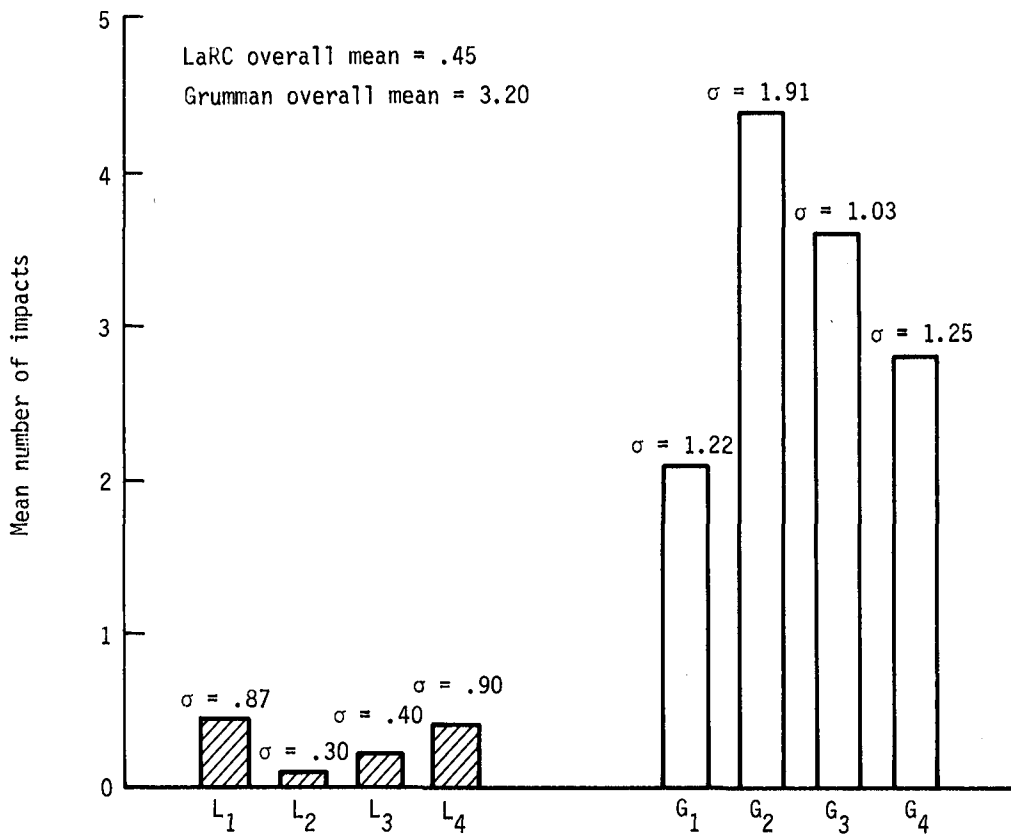


Figure 19.- Number of impacts for indirect-view tests with 0.500-in. peg and resolved-rate control.

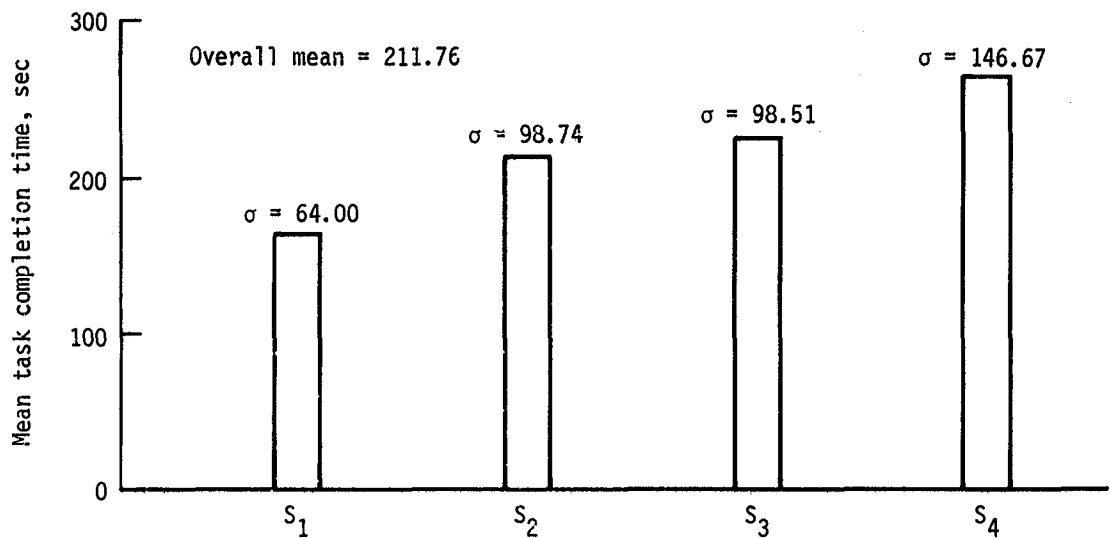


Figure 20.- Task completion times for indirect-view tests with all variables considered.

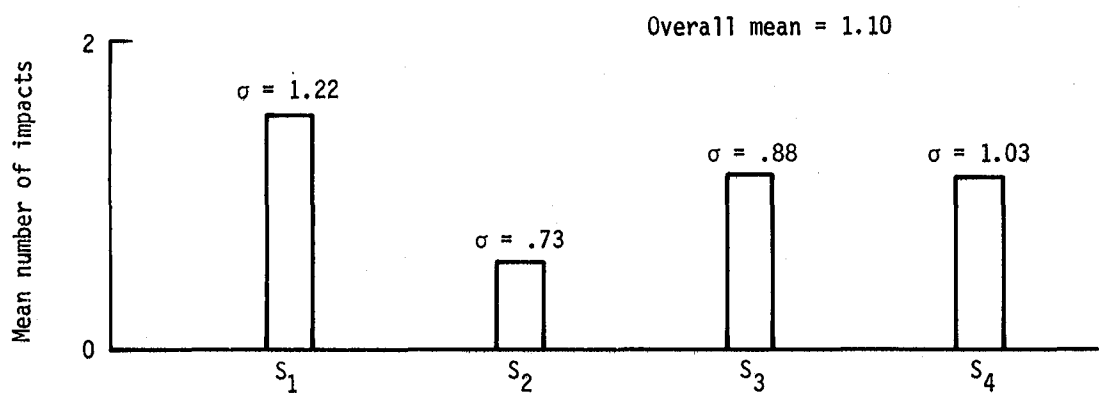


Figure 21.- Number of impacts for indirect-view tests with all variables considered.

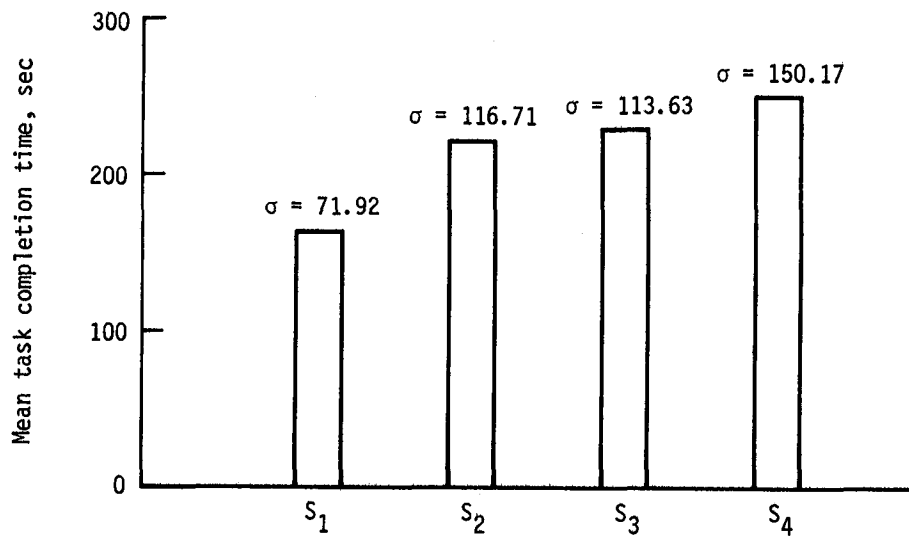


Figure 22.- Task completion times for LaRC subjects for combined direct- and indirect-view data.

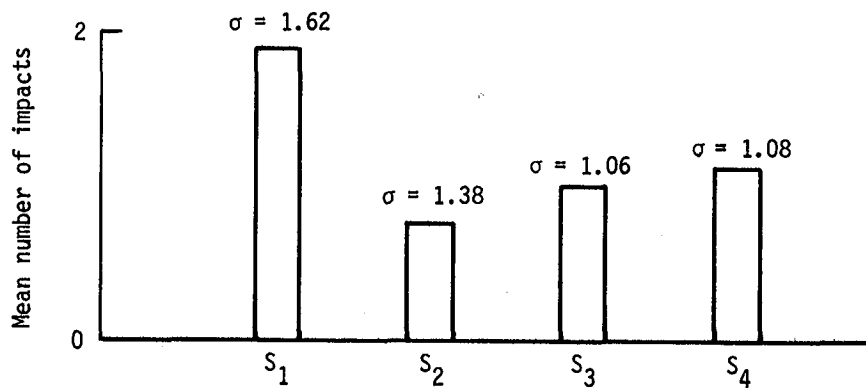


Figure 23.- Number of impacts for LaRC subjects for combined direct- and indirect-view data.

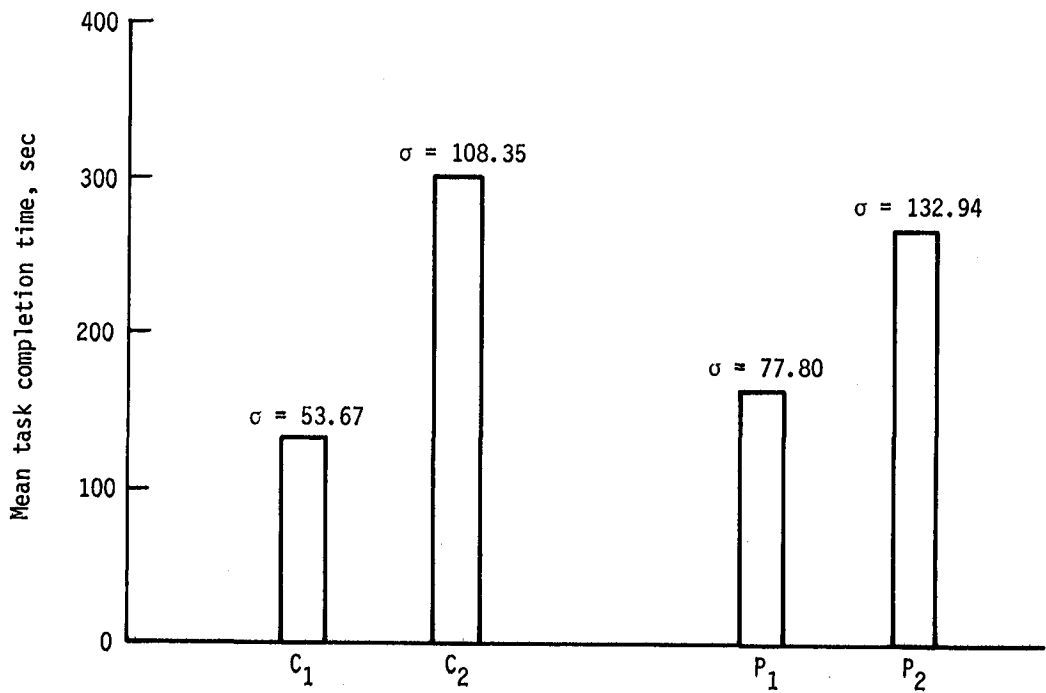


Figure 24.- Effect of control mode and peg size on task completion times for all direct- and indirect-view data.

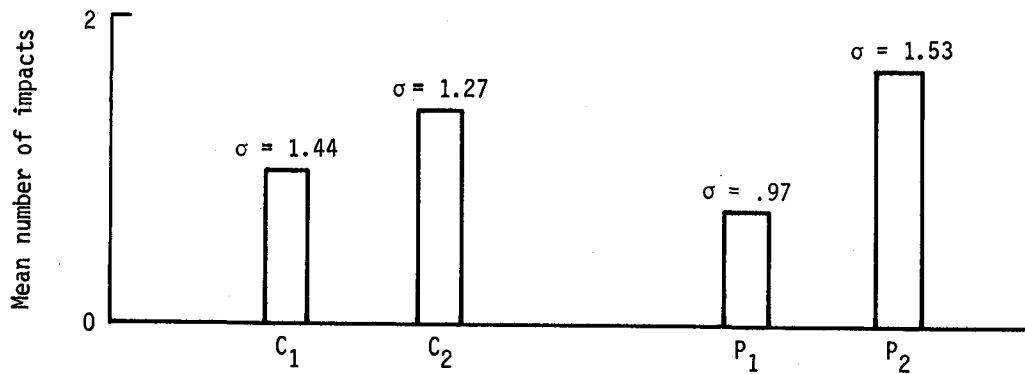


Figure 25.- Effect of control mode and peg size on number of impacts for all direct- and indirect-view data.

1. Report No. NASA TP-2547		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Baseline Experiments in Teleoperator Control				5. Report Date July 1986	
				6. Performing Organization Code 506-45-21-01	
7. Author(s) Walter W. Hankins III and Randolph W. Mixon				8. Performing Organization Report No. L-15963	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665-5225				10. Work Unit No.	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001				13. Type of Report and Period Covered Technical Paper	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract <p>Studies have been conducted at the NASA Langley Research Center (LaRC) to establish baseline human teleoperator interface data and to assess the influence of some of the interface parameters on human performance in teleoperation. As baseline data, the results will be used to assess future interface improvements resulting from this research in basic teleoperator human factors. In addition, the data have been used to validate LaRC's basic teleoperator hardware setup and to compare initial teleoperator study results. Four subjects controlled a modified industrial manipulator to perform a simple task involving both high and low precision. Two different schemes for controlling the manipulator were studied along with both direct and indirect viewing of the task. Performance of the task was measured as the length of time required to complete the task along with the number of errors made in the process. Analyses of variance were computed to determine the significance of the influences of each of the independent variables. Comparisons were also made between the LaRC data and data taken earlier by Grumman Aerospace Corp. at their facilities.</p>					
17. Key Words (Suggested by Author(s)) Manipulators Man-machine interface Teleoperation Validation Automation Human operator Workload				18. Distribution Statement Unclassified - Unlimited Subject Category 54	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 63	22. Price A04		

**National Aeronautics and
Space Administration
Code NIT-4**

**Washington, D.C.
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